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DYNAMIC CHARACTERISTICS OF TWO 300 KW CLASS DUAL KEEL SPACE STATION CONCEPTS

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SUMMARY

This paper presents some results from an investigation of the dynamic behavior of a 300 kw class, solar dynamic powered, dual keel space station. The purpose of the investigation was to determine and assess the influence of truss bay size on station controllability during rigid body attitude adjustment and orbit reboost maneuvers. Two cases were studied, one in which the space station was comprised of a truss with five meter bays and a second, where the bay size was nine feet. To insure that any difference in the vibration characteristics would be due solely to the difference in truss size, the two space station configurations were defined to minimize differences in overall dimensions and attached payloads and subsystems. This paper contains the space station concept definition, an evaluation of the lower modes and natural frequencies, and some results of a transient analysis due to an orbit reboost maneuver.

Rigid body characteristics between the two models showed excellent agreement with total mass differing by only .2% and principle mass moments of inertia differing by a maximum of 4%. For corresponding flexible body truss modes, frequencies for the station with 5m bays were approximately 1.8 times the frequencies of the station with 9-foot bays. When subjected to an orbit reboost maneuver, transient response studies showed the maximum rotation at

the outboard solar collector for the station with 9-foot bays (at .0955°) to be three times the maximum rotation for the station with 5m bays.

INTRODUCTION

This paper presents some results from an investigation of the dynamic behavior of a 300 kw class, solar dynamic powered, dual keel space station. The purpose of the investigation was to determine and assess the influence of truss bay size on station controllability during rigid body attitude adjustment and reboost maneuvers. Two cases were studied, one in which the space station was comprised of a truss with five meter bays and a second where the bay size was nine feet. This paper contains the definition of the space station concepts, an evaluation of their lower modes and natural frequencies, and results from a transient response analysis of an orbit reboost maneuver. The control aspects of the investigation are presented in a companion paper, reference 1.

The dynamic characteristics of the station concepts presented on this paper were used in the control study presented in the companion paper to evaluate control stability for attitude control and to investigate control stability during a closed-loop reboost maneuver. A result of the companion study was the definition of an open-loop rigid body orbit reboost control law for each of the two space station concepts.

The transient response analysis presented is based on these control laws and focuses on the dynamic response of the solar dynamic power system during reboost. The solar dynamic system has several active controllers which are designed to keep the angle between the concentrator symmetry axis and the solar vector within 0.1° during any disturbance applied to the station. In

order to measure the effect of the truss bay size on the flexible response of the station due to the reboost maneuver, all controllers are assumed inactive and locked, so that the uncontrolled variation in time of the viewing angle is determined.

Since the primary concern of this study was the effect of truss depth on the power system response, the two space station configurations were designed to be as identical as possible in terms of keel spacing, overall dimensions, structural components and material properties, and subsystem and payload masses and locations. Since the dual keel concept was still in the definition phase at the time of this study, compromises were made in these areas between existing concepts that were under study by the two primary phase B contractors concerned with the truss structure definition (Rockwell International and McDonnell Douglas). Information used to formulate the space station concept presented in this paper was obtained from various sources including the NASA Space Station Reference Document, reference 2, data releases from the phase B contractors, NASA Johnson Space Center and the NASA Lewis Research Center.

In order to perform the study, detailed finite element models were developed for both the station with 9-foot bays bays and the station with 5m bays. Descriptions of the two dual keel configurations along with information pertaining to subsystems and attached payloads are presented. Information on both stations' rigid body and vibration mode characteristics are also given. Finally, results of the transient response studies are summarized and performances of the two space station configurations are assessed.

DESCRIPTION OF 9 FOOT AND 5 METER DUAL KEEL MODELS

Finite element models have been constructed for both the 9 foot (9') and the 5 meter (5m) truss configurations. A description of the dimensions, structural components, and masses and locations of attached subsystems for these configurations follows. Additionally, information on finite element representation of these configurations is given.

Model Dimensions

Figures 1 and 2 are drawings of both models showing their major dimensions. As mentioned previously, a primary concern in developing these configurations was to maintain major dimensions as close as possible so that differences in dynamic characteristics would be attributable only to truss depth and not model configuration. As seen from figures 1 and 2, these dimensions agree within seven percent between the two models.

On the 9' model, the center line of the inboard pair of solar dynamic reflectors is 180' from the station origin and the spacing between the inboard and outboard reflector pairs is 81'. On the 5m model, the inboard reflectors are 180.4' from origin and adjacent pairs are separated by 82'. The reflectors are spaced far enough apart so that they do not shadow each other. The amount of spacing is determined by the maximum beta angle and the reflector diameter.

For the 9' model, each alpha rotary joint occupies one bay of the transverse boom, and their centers are 135' from the origin of the station along the Y axis. On the 5m model, each alpha rotary joint is two bays long, and their centers are 139.4' from the station's origin. The beta rotary joints for the solar dynamic reflectors each occupy one bay on both models.

Therefore their centers are 9' and 16.4' from the center line of the transverse boom (Y axis) for the 9' and 5m models, respectively.

Finally, the two central radiators for both models are cantilevered from the back face (-X direction) of the transverse boom inboard of the rotary joint. The locations of these radiators are 108' and 114.8' in the Y direction from the station's origin for the 9' and the 5m models, respectively.

Structural Description

The truss bay geometry used in both models is shown in figure 3 and is referred to as an orthogonal tetrahedral truss. All truss members, as well as the support beams for the Reaction Control System (RCS) and the pressurized modules, are modeled to represent graphite/epoxy tubes with a two inch outer diameter, 0.06 inch wall thickness, and a Young's modulus of 30×10^6 psi. All joints are assumed to be perfect, that is giving no stiffness reductions and exhibiting linear behavior.

There are a few places in the models where rigid, massless beams are used to represent structure that is assumed to be significantly stiffer than the truss structure. The control moment gyro (CMG), which is located in the center bay of the transverse boom, has eight rigid members connecting the eight corner joints of that bay to a joint in the center of the bay (origin of the coordinate system). Controller inputs are made at this center joint. Also, the faces of the bays in the transverse boom on which the central radiators are mounted have four rigid members connecting the four truss joints to a central joint from which the radiator is cantilevered (see figure 4). Finally, all satellite servicing hangers and storage facilities are represented by joints located at what would be the center of gravity of the

actual facility and given appropriate masses and moments of inertia. Each joint is connected to the truss by a pyramid arrangement of four rigid beams. By using this approach, the stiffening effect that these facilities have on the truss is approximated.

Figure 5 shows a typical solar dynamic power conversion unit of the type considered for this model. The principle components of such a unit are the reflector dish, the power collector and converter, the power radiator, and the supporting truss structure. For this analysis, the solar dynamic units are modeled as rigid beams with joints located at the center of the reflector dish and the center of the collector/converter unit (figures 6 and 7). The geometry of the offset support structure for the solar dynamic units arises from the desire to maintain the center of gravity of each pair of solar dynamic units on the center line of the transverse boom. This avoids possible operational problems that might arise from shifts in the station's center of gravity during rotation of the power units. Assuming one bay for the beta rotary joint, whole bays for the design of the offset structure, and allowing for clearance of the 53.1' diameter reflector dish, the center of the dish will be 54.0' and 73.8' from the centerline of the transverse boom (Y axis) for the 9' and the 5m designs, respectively. It is believed that this difference in offset distances could affect the transient response results calculated at the center of the reflectors. Since other offset support structure geometries may exist which would reduce these distances, to maintain consistency, the 5m model is configured to allow the reflector centers to be moved one bay (16.4') toward the transverse boom. This makes the distance between the reflectors and the boom center for the 5m model 57.4', which more closely compares to the 54.0' distance used for the 9' model.

Other structural members have been modeled as beams with properties representative of the actual component as described in reference 2. Referring again to figure 4, the support booms for the radiators are 30' long aluminum tubes with an outer diameter of 24" and a wall thickness of 0.1". The radiators are modeled with two node beam elements, 50 feet long and having cross sectional properties of a 105' by 1.306" aluminum box, with .047" thick walls. The pressurized modules are also modeled as beams with the cross sectional properties of an aluminum cylinder, 14.5 feet in diameter with .115 inch thick walls, and are arranged as shown in figures 8 and 9.

For both models, the modules are supported off of "t" shaped truss booms that extend from the center bay of the central transverse boom (see figures 8 and 9). Because of the large mass of the module cluster, the torsional flexibility of the central section of the transverse boom was anticipated to be unacceptably high. Therefore, two more truss booms have been added to the models between the keels, one above and one below the transverse boom, and these booms have been connected to the center bay of the transverse boom with typical truss bays to increase the stiffness in this area.

Finally, the alpha and beta rotary joints are assumed to have identical designs that represent large diameter, discrete bearing rings with 24 member truss-type transition structures as described in reference 3. The rings are modeled as six inch square aluminum box beams with 0.25 inch thick walls and are 9' and 14' in diameter for the 9' and the 5m trusses, respectively. The transition structure is made of graphite/epoxy tubes with cross sectional areas determined using methods found in reference 3. For the 9' alpha and beta rotary joints, which are both one bay long due to packaging requirements, the cross sectional area of each transition truss member is twice the area of

the truss struts (or .7314 in^2). For the 5m rotary joint the area of the transition truss members is .600 in^2 and 1.463 in^2 for the alpha and the beta joint trusses, respectively.

Component Mass Description

A summary of structural component masses is given in table 1. The mass information is presented as element structural and non-structural lineal densities (volumetric density times cross sectional area), total lineal density, element length, and total element mass. For components made up of more than one element (ie. truss structure) only a total length and mass is given. Truss members are assumed to be graphite/epoxy with a density of 0.063 lbm/in^3 and all other elements are assumed to be aluminum with a density of 0.10 lbm/in^3.

Table 2 is a summary of the station's subsystems, their approxomite locations, and corresponding masses. These subsystems are represented by point masses or a series of point masses distributed on the structure, as shown in figures 10 and 11. Each entry in the table includes the number of joints at which the subsystem mass is distributed and the corresponding mass per joint that is applied. Most subsystems are concentrated at a few neighboring joints, except for the power management and distribution system (PMAD) and truss joint mass which are distributed along the truss at every truss joint.

A set of scientific instruments and payloads has also been included in the models and are represented by attached rigid masses. This set is illustrated in figures 12 and 13, and is listed in table 3 along with the number of nodes that each payload is distributed on, and the total mass and the approximate location of the payloads. Included are non-pressurized

Canadian and Japanese experiment modules that are assumed to be located in the vicinity of the pressurized module cluster.

Table 4 summarizes mass information on hangers and servicing facilities for satellites, orbital transfer vehicles (OTVs), and orbital maneauvering vehicles (OMVs). As indicated previously, these facilities are represented by rigid masses (which include appropriate mass moments of inertia) and are located off of the structure by rigid beam support pyramids. The masses, moments of inertia, and exact locations af these facilities are included in table 4 and their locations are shown in figures 12 and 13.

Finite Element Representation

Figures 14 and 15 show the finite element models of the two space station configurations defined. The 9' model had 1159 joints, with 235 beam elements, 3485 truss (axial stiffness only) elements, and a total of 3510 dynamic degrees of freedom (DDOF). The 5m model had 735 joints, 235 beam elements, 2110 truss elements, and 2238 DDOF. The difference in model size (DDOF) was due to the difference in truss bay size.

SPACE STATION DYNAMIC CHARACTERISTICS

Rigid Body Properties

The center of gravity, measured from the origin, and the mass properties are listed in Table 5 for the 9 foot truss model and both 5 meter truss models (solar reflectors in and out). In order to insure that any differences in the dynamic behavior of the models would be due only to the truss bay size, the rigid body characteristics had to be made as close to equal as possible. In fact, operational requirements for the various systems and sub-systems on each

configuration were considered secondary in importance to matching the rigid body properties of the models. The center of gravity (c.g.) locations along the X and Y axes agree to within 1%. The relatively large difference in c.g. location (11%) for the Z axis is primarily due to a difference of 55 inches in the Z direction location of the OTV hanger (190,000 lbm) for the 9 foot and 5 meter models. The total mass of the two configurations agree to within .2%, while the principle mass moments of inertia agree to within 4% for the 9 foot model and the 5 meter model with solar reflectors in.

Flexible Body Properties

<u>Mode Shape Description for the Full Truss Models</u>. - The first 60 modes and frequencies were calculated for the 9'model, the 5m model with solar reflectors in, and the 5m model with solar reflectors out. The first 15 elastic modes and frequencies are summarized for each of the configurations in table 6 (note, modes 1-6 are rigid body modes). Descriptions of the mode shapes are denoted by letters that are defined in the accompanying key. These descriptions summarize only the primary structural motion in the mode shape, and in many cases the primary motion is coupled with secondary structural motion, such as radiator bending, for example. The fundamental truss modes for the 9 foot model and the 5 meter model (with reflectors in) are shown in figures 16A and 16B. The fundamental mode for the 9 foot model is primarily composed of symmetric transverse boom bending about the Z-axis, with some transverse boom bending about the X-axis and torsion about the Y-axis. The fundamental truss mode for the 5 meter model (reflectors in) is the same as the 9' model fundamental mode.

In figure 16C, the frequencies for the two 5m configurations (reflectors in and out) are compared. These results illustrate sensitivity of the space

station flexible modes to the location of the solar dynamic reflectors. The letters associated with the frequencies refer to the mode shape descriptions introduced in table 6. By moving the solar dynamic reflectors out, the mass moment of inertia of the transverse boom about its longitudinal (Y) axis is increased and, thus, the torsional frequencies of the transverse boom (modes E,F,N,O) are decreased on the average of 18%. Other structural frequencies (modes C,D,I,J,K,L,M) decreased by an average of 3%.

In figure 17A, the first 15 frequencies below 0.4 hz for the 9' and 5m (reflectors in) configurations are shown. As expected, the radiator natural frequencies (modes A,B,G,H) are nearly the same for the two configurations because the radiators are modeled the same way in both stations. Also, for corresponding primary truss structure modes, the 5m model frequencies are approximately a factor of 1.82 greater than the frequencies of the 9' model. Since some of the truss structure frequencies of the 9' model are close to the fundamental radiator frequencies, there is some coupling between these modes for the 9' model.

Effect of Removing the Vertical Truss Bays. - In this study, the vertical truss structure which is located at the center of the transverse boom was removed from the 5m model (with reflectors in) and the 9' model. The purpose of this analysis was to investigate the sensitivity of mode M (as described in Table 6) to the local stiffness provided by the vertical truss bays in the vicinity of the module cluster. This mode is considered important because micro-g acceleration levels are desired at the module location and because sensors for the attitude control system are located in that area (see refrence 2). The corresponding shape for mode M is shown in figure 17B for the 5 meter model (reflectors in) and is characterized primarily by the module cluster

(see figures 7 and 8) rotating about the transverse boom (Y axis). To determine the sensitivity of mode M to this local stiffness, the vertical truss bays connecting the transverse boom to the booms above and below it (see figures 1 and 2) were removed and new modes and frequencies were calculated. With the vertical truss bays removed, the frequency of mode M decreased by 53% (from 0.185 hz to 0.086 hz) for the 9' bay model and by 45% (from 0.339 hz to 0.188hz) for the 5m bay model. Other frequencies were changed by this reduced stiffness in the module cluster area, but the changes were generally less than 2%.

<u>Effect of Reduced Truss Member Stiffness</u>. - In this study, the baseline value of Young's Modulus (30×10^6 psi) for all of the truss members in the 9' model was reduced by 50%. The purpose of this study was to assess the sensitivity of the frequencies of the truss structure modes to a reduction in truss member stiffness. This stiffness reduction could occur if Young's Modulus turned out to be less than 30×10^6 psi in the truss members or if the truss joints turned out to be less stiff than the truss members. The analysis was conducted by reducing the modulus of elasticity of the truss members in the 9' bay configuration by 50%, from 30×10^6 psi to 15×10^6 psi, and calculating new modes and frequencies for this more flexible structure. The material and section properties for all of the other structural components remained as described earlier in this paper. The frequencies were reduced by approximately 30% from the frequencies of the original structure because of the reduced modulus. In Figure 18, mode M is shown as a function of the truss bay bending stiffness for the 5 meter bay model, the 9 foot bay model and the 9 foot bay model with a 50% reduction in truss member stiffness. The slope of the curve shows that

the frequency for mode M is more sensitive to changes in stiffness for the 9' bay configuration than for the 5m bay configuration.

TRANSIENT RESPONSE RESULTS

Orbit Reboost Loading

In the orbit reboost maneuver, the four RCS thrusters are fired along the flight path (in the -X direction) to increase the orbital velocity and thus make up for altitude lost due to atmospheric drag. Since the upper and lower pairs of RCS thrusters are not located equidistant along the Z axis from the space station c.g., simultaneous firing of all four thrusters causes the station to rotate about the Y axis. In order for the space station to maintain a 1^{o} local vertical attitude pointing requirement during reboost, the upper thrusters are fired continuously while the lower thrusters are fired on and off as shown in figure 19. The thruster firing sequences shown in figure 19 are for the 5m station, and are designed to maintain a 1^{o} attitude constraint with a $.05^{o}$ hysteresis (see reference 2). The firing sequences shown in figure 19a represent the first 500 seconds (start-up period) of the orbit reboost maneuver. During this time, there is a decrease in each successive lower thruster firing duration as the firing sequence approaches limit cycle. At limit cycle, the lower thrusters are on for 59.06 seconds of the 73.59 second period for the 5m station (see figure 19b) and 54.44 seconds of the 69.56 second period for the 9' station.

Station Response

In general, the time required to reach the orbit reboost limit cycle from the beginning of the firing sequence is on the order of thousands of seconds. Understanding the space station response to the orbit reboost maneuver

however, requires only that the reboost start-up and the actual limit cycle be studied in a transient response analysis. The start-up period is considered because the initial transient responses might be large. Limit cycle is considered since it is a constant period, oscillating forcing function and thus has the potential of causing resonance with a natural vibration mode and corresponding large amplitude responses.

The elastic dynamic response (ie. no rigid body motion included) of both the 5m and the 9' space stations subjected to both the orbit reboost start-up transient and the orbit reboost limit cycle were studied. For both models, modes 7-50 were used in the dynamic response calculations and 1/2 % damping was assumed for each mode. For this study, the particular point in the orbit chosen to study was where the solar dynamic collectors are in the maximum drag configuration.

Of particular interest in this study, were the rotations at the solar dynamic collectors because the amount of rotation at the collectors affects the power system performance. (Satisfactory performance of the power system requires that the collectors not rotate more than 0.1^{o} from the solar vector). Since for this particular configuration (maximum solar dynamic collector drag), the space statioin X axis, the solar vector, and a normal at the center of the collectors are all parallel, the total rotation at the collector can be defined as $(\theta_Y^2 + \theta_Z^2)^{1/2}$. The locations where transient response quantities were measured are shown in figure 20 for the 5m and 9' stations. The inboard collectors are 1240 (arrays in), 1250 (arrays out), and 1244, and the outboard collectors are 1440 (arrays in), 1450 (arrays out), and 1444 for the 5m and 9' stations respectively.

Table 7 summarizes the maximum total rotation (in degrees) obtained for the three models (9', 5m with arrays in, and 5m with arrays out) subjected to the orbit reboost start-up transient and limit cycle. The table shows first of all, that none of the collectors on any of the three station configurations studied violated the 0.1° pointing requirement (although the 9 ft. station outboard collector comes very close at $.0955^{\circ}$). Second, for the case where the 5m station and the 9' station collectors are at the same +Z locations (5m arrays in), the maximum rotation at the 9' station collectors is 3.3 to 3.5 times the maximum rotation at the 5m collectors for the transient start-up, and 2.7 to 2.9 times for the limit cycle. Third, for the case of 5m with the arrays out, displacements at the collectors are 1.4 to 1.6 times the displacements for the 5m with the arrays in for the reboost maneuver.

As was mentioned in the preceeding section, modes were obtained for a version of the 9' model where the baseline Young's modulus for the truss members was decreased by a half to 15.0×10^{6} lbf/in^{2}. The maximum elastic rotation at the outboard collector for this version of the 9' station was 0.2°, or, twice the maximum allowable. In figure 21, the maximum elastic rotation at an outboard collector due to orbit reboost is shown as a function of the space station truss bending stiffness (Young's modulus x truss cross sectional moment of inertia). The rotation varies inversely with stiffness with a 50% reduction in truss stiffness for the 9' station resulting in a doubling of the collector deflection. What is most important about the figure however, is that the slope of the curve at the 9' bay stiffness is much steeper than the slope at the 5m bay stiffness which means that collector pointing errors on the 9' station are more sensitive to degredation of truss stiffness. The figure also shows that, because of its proximity to the

pointing requirement, any reduction in stiffness will cause the 9 ft station to violate the pointing requirement.

CONCLUDING REMARKS

This report presents results of dynamic and transient response analyses performed on a 300 kw class solar dynamic dual keel space station. In order to assess the effect of truss structure bay size (stiffness) on station controllability, two cases were studied; one where the space station truss had 5m bays, and another where the bay size was 9 feet. To insure that any difference in the vibration characteristics would be due solely to the difference in truss size the two space station configurations were defined to minimize differences in overall dimensions and attached payloads and subsystems. As a result, excellent agreement was obtained for rigid body characteristics, with total mass for the two models differing by .2% and principle mass moments of inertia differing by a maximum of 4%.

For corresponding mode shapes of the two stations which consisted primarily of truss structure motion, the frequencies for the station with 5m truss bays were approximately 1.8 times the frequencies for the station with 9' bays. For both stations, the fundamental truss structure mode was transverse boom bending with a frequency of .123 hz for the station with 5m bays and .062 hz for the station with 9' bays. A mode which consisted primarily of rotation of the module clusters about the Y axis was investigated in more detail because it influences motion at the location of the attitude control sensors as well as motion at the modules. The frequency of this mode was more sensitive to small changes in truss stiffness for the station with 9' bays than for the station with 5m bays.

When subjected to an orbit reboost maneuver, transient response studies performed on the two stations indicated that rotations at the solar dynamic collectors were greatly influenced by the truss size. In particular, the station with 9' bays had a maximum rotation at the solar collector that was three times greater than that of the station with 5m bays even though the truss bending stiffness was only approximately 1.8 times less. Also, the maximum rotation at an outboard solar dynamic collector is more sensitive to small variations in truss stiffness for the station with 9' bays than for the station with 5m bays.

REFERENCES

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2. Space Station Reference Configuration Description. JSC 19989, August 1984.

3. Lake, Mark S; Bush, Harold G.: An Analytical Investigation of a Conceptual Design for the Space Station Transverse Boom Rotary Joint Structure. NASA TM 87665, January 1986.

TABLE 1.- STRUCTURAL MASS SUMMARY

STRUCTURAL ELEMENT	LINEAL DENSITY (lbm/in) Structural	Non-structural	Total	LENGTH (in)	TOTAL MASS (lbm)
Truss Members					
9' truss	0.0230	0.000	0.0230	422752.5	9723.3
5m truss	0.0230	0.000	0.0230	420807.0	9678.6
Modules					
HAB 1	6.281	56.37	62.651	522.0	32703.8
HAB 2	6.281	54.38	60.661	522.0	31665.0
HAB 3	6.281	56.37	62.651	522.0	32703.8
HAB 4	6.281	54.38	60.661	522.0	31665.0
LAB 1	6.281	69.25	75.731	522.0	39427.2
LAB 2	6.281	125.45	131.736	522.0	68763.6
LAB 3	6.281	69.25	75.731	522.0	39427.2
LAB 4	6.281	125.45	131.736	522.0	68763.6
LOG 1	6.281	70.43	76.711	522.0	40043.2
LOG 2	6.281	70.43	76.711	522.0	40043.2
Japanese	6.281	66.31	72.591	594.0	43119.1
Airlocks	6.281	37.50	43.781	1512.0	66196.9
			(total of 12 airlocks)		
Tunnels					
9' truss	6.281	0.000	6.281	3888.0	24420.5
5m truss	6.281	0.000	6.281	4724.0	29666.4
			(total of 12 tunnels)		
Radiators	11.86	14.87	26.73	1200.0	32076.0
Radiator Booms	0.751	0.000	0.751	720.0	541.6
Rotary Joints	(total of 10 joints on the station)				
9'Truss					
ring	0.60	0.00	0.60	3393.0	2036.0
truss struts	0.046	0.00	0.046	16895.0	777.2
5m truss					
ring	0.60	0.00	0.60	5278.0	3167.0
truss struts					
(beta)	0.092	0.00	0.092	25134.3	2312.4
(alpha)	0.038	0.00	0.038	11920.7	453.0
				TOTAL - 9'	604095.6
				- 5m	612416.0

TABLE 2.- SUBSYSTEM MASS SUMMARY

SUBSYSTEM	LOCATION	MASS/NODE	NODES	TOTAL MASS(lbm)
CMG	Central Boom	7468.8	1	7468.0
RCS	Keels	54.0	4	216.0
Hydrazine	With RCS	434.4	32	13902.0
Alpha/Beta Mechanisms	Trans. Boom	125.0 (Total of 10 joints on station)	80	10000.0
Solar Converter	Trans. Boom	6261.0 (Total of 8 units on station)	8	50088.0
Solar Reflector	Trans. Boom	7803.0 (Total of 8 units on station)	8	62424.0
MRMS	Keel	1250.0	4	5000.0
TCS	Central Boom			
	9' Truss	100.25	24	2406.0
	5m Truss	171.9	14	2406.0
PMAD	Around Truss			
	9' Truss	4.22	948	4000.0
	5m Truss	7.30	548	4000.0
Truss Joints	Around Truss			
	9' Truss	10.0	948	9480.0
	5m Truss	5.0	548	2740.0
ORU & Tools	Left Upper Keel	2333.3	6	14000.0
<u>Antennas</u>				
TDRSS	Upper Boom	310.0	2	620.0
Prox-Ops.	Lower Keels	74.0	2	148.0
Co-Orb/Med.	Lower Keels	416.0	1	416.0
Co-Orb/High	Lower Keels	216.0	1	216.0
Radar	Lower Keels	500.0	1	500.0
			TOTAL - 9'	180884.0
			- 5m	174144.0

TABLE 3.- PAYLOAD MASS SUMMARY

TITLE	LOCATION	MASS/NODE	NODES	TOTAL MASS(lbm)
SAAX-0011	Upper Boom	6890.8	4	27563.0
SAAX-0001	Upper Boom	1698.8	4	6795.0
S-003	Upper Boom	1102.3	4	4409.0
TDMX-2441	Upper Boom	110.3	4	441.0
S-004	Upper Boom	275.5	4	1102.0
TDMX-2541	Upper Boom	4410.0	4	17640.0
SAAX-0021	Upper Boom	3114.0	4	12456.0
TDMX-2001	Upper Boom	512.5	4	2050.0
SAAX-0207(1)	Upper Boom	716.8	4	2867.0
SAAX-0207(2)	Lower Boom	1433.5	4	5734.0
SAAX-0251	Lower Boom	234.3	4	937.0
TDMX-4007	Lower Boom	55.3	4	221.0
SAAX-0250	Lower Boom	17.5	4	70.0
SAAX-0207(3)	Lower Boom	716.8	4	2867.0
TDMX-4002	Lower Boom	342.0	4	1368.0
Canadian expt.	Module Boom	6350.0	4	25000.0
Japanese expt.	Module Boom	3245.0	4	12980.0
			TOTAL	124500.0

TABLE 4.- HANGER AND SERVICING FACILITY MASSES AND LOCATIONS

TITLE 9' Truss - 5m Truss -	IXX xcg xcg	IYY ycg ycg	IZZ(lbm*in^2) zcg (in) zcg	MASS(lbm)
OMV Servicing Hanger	1.30E+9 0.0 0.0	1.30E+9 756.0 850.8	1.56E+8 1566.0 1574.4	45000.0
Satellite Service Facility	2.59E+9 0.0 0.0	2.59E+9 270.0 276.0	7.98E+8 -1080.0 -1082.0	37000.0
Satellite Storage Facility	2.59E+9 0.0 0.0	2.59E+9 -270.0 -276.0	7.98E+8 -1080.0 -1082.0	37000.0
Satellite Refueling Facility	2.59E+9 0.0 0.0	2.59E+9 -810.0 -904.8	7.98E+8 -864.0 -885.2	37000.0
Satellite Instrument Storage	4.87E+8 0.0 0.0	1.91E+9 810.0 904.8	2.09E+9 -594.0 -590.4	30000.0
OTV & Hanger	1.93E+10 0.0 0.0	5.12E+10 0.0 0.0	5.12E+10 1728.0 1672.8	190000.0
			TOTAL	376000.0

TABLE 5.- TOTAL MASS PROPERTIES OF DUAL KEEL CONFIGURATIONS

	9' TRUSS	5M TRUSS (Reflectors In)	5M TRUSS (Reflectors Out)
Center of Gravity (in)	x=123.1 y= 45.5 z=126.4	x=122.0 y= 45.9 z=112.0	x=122.0 y= 45.9 z=112.0
Total Mass (lbm)	1,285,000	1,287,000	1,287,000
Mass Moments of Inertia ($lbm x in^2$)	Ixx= 2.346E+12 Iyy= 1.427E+12 Izz= 1.397E+12 Ixy= 3.218E+9 Ixz= 2.885E+10 Iyz=-2.706E+10	Ixx= 2.403E+12 Iyy= 1.436E+12 Izz= 1.453E+12 Ixy= 2.528E+9 Ixz= 2.769E+10 Iyz=-4.076E+10	Ixx= 2.438E+12 Iyy= 1.471E+12 Izz= 1.453E+12 Ixy= 2.528E+9 Ixz= 2.769E+10 Iyz=-4.076E+10

TABLE 6.- FIRST 15 ELASTIC FREQUENCIES AND MODE SHAPES

MODE NO.	FREQUENCY - hz. (MODE SHAPE)		
	9' TRUSS	5m Truss (Refl. in)	5m Truss (Refl. out)
7	.0623 (C)	.0794 (A)	.0791 (A)
8	.0682 (D)	.0804 (B)	.0803 (B)
9	.0701 (E)	.1235 (C)	.1131 (C)
10	.0760 (A)	.1321 (D)	.1234 (E)
11	.0833 (B)	.1483 (E)	.1266 (D)
12	.0918 (F)	.1631 (F)	.1407 (F)
13	.0947 (I)	.1709 (G)	.1624 (I)
14	.1168 (J)	.1740 (H)	.1708 (G)
15	.1263 (K)	.1756 (I)	.1734 (H)
16	.1562 (L)	.2225 (J)	.2203 (J)
17	.1615 (H)	.2355 (K)	.2338 (K)
18	.1623 (G)	.2870 (L)	.2839 (L)
19	.1852 (M)	.3387 (M)	.3079 (N)
20	.2158 (N)	.3898 (N)	.3091 (O)
21	.2168 (O)	.3906 (O)	.3376 (M)

MODE SHAPE KEYS:

A - First radiator y bending (out of phase)
B - First radiator y bending (in phase)
C - First transverse boom z bending (symmetric)
D - First transverse boom x bending (symmetric)
E - First transverse boom torsion (symmetric)
F - First transverse boom torsion (antisymmetric)
G - First radiator z bending (in phase)
H - FIrst radiator z bending (out of phase)
I - First transverse boom x bending with torsion (antisymmetric)
J - Second transverse boom z bending
K - First keel y bending
L - First keel y bending (anticlastic plate mode)
M - First module support torsion with upper keel y bending
N - Second transverse boom torsion (symmetric)
O - Second transverse boom torsion (antisymmetric)

TABLE 7.- MAXIMUM TOTAL ELASTIC ROTATIONS DUE TO ORBIT REBOOST

	Maximum Total Rotation $\sqrt{\theta_Y^2 + \theta_Z^2}$, deg			
	Start-up Transient		Limit Cycle	
Model	Inboard Concentrator	Outboard Concentrator	Inboard Concentrator	Outboard Concentrator
9'	.0716	.0955	.0602	.0761
5m (Arrays In)	.0209	.0283	.0211	.0282
5m (Arrays Out)	.0293	.0415	.0292	.0437

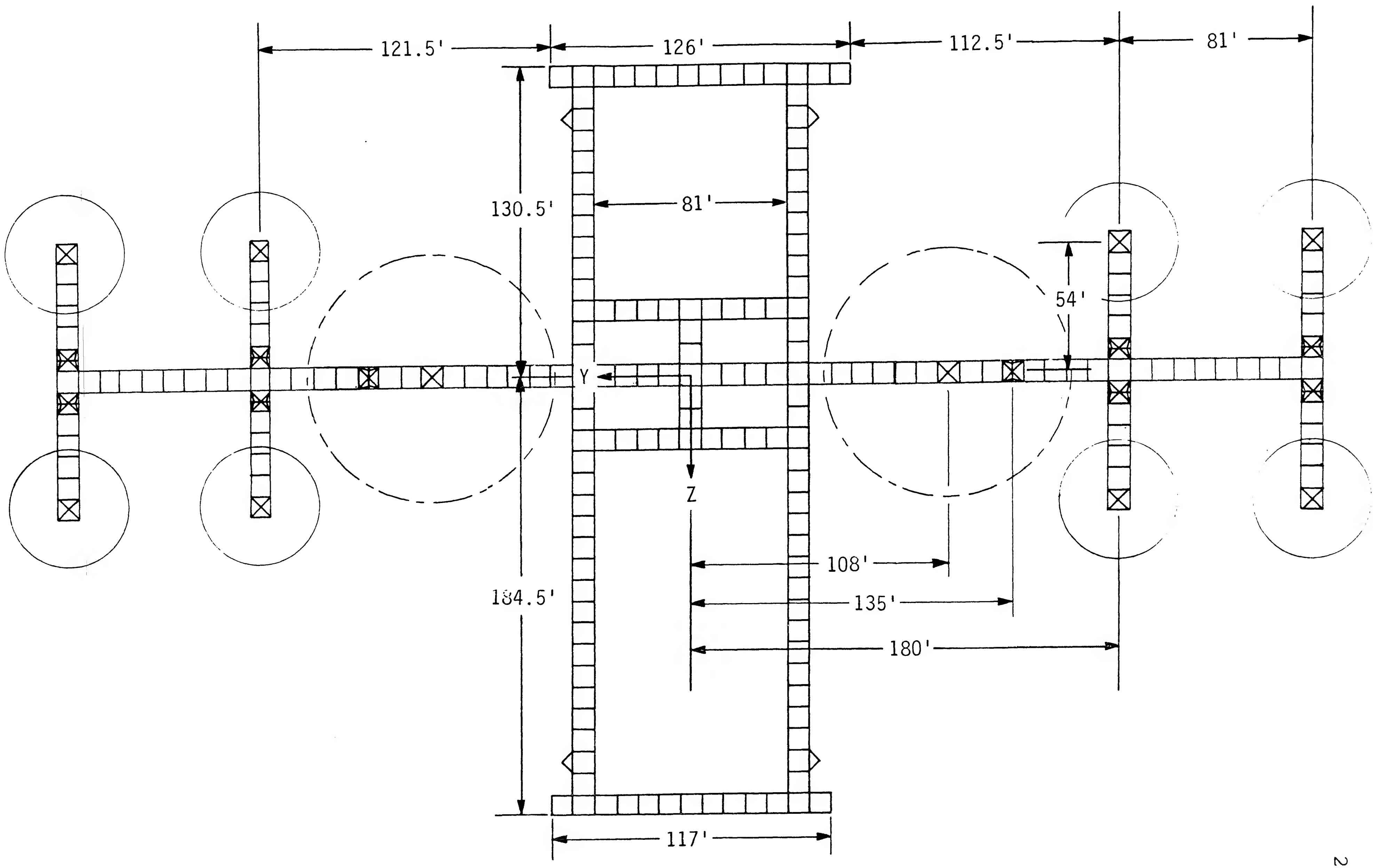


Figure 1.- 9' Truss Dual Keel Space Station.

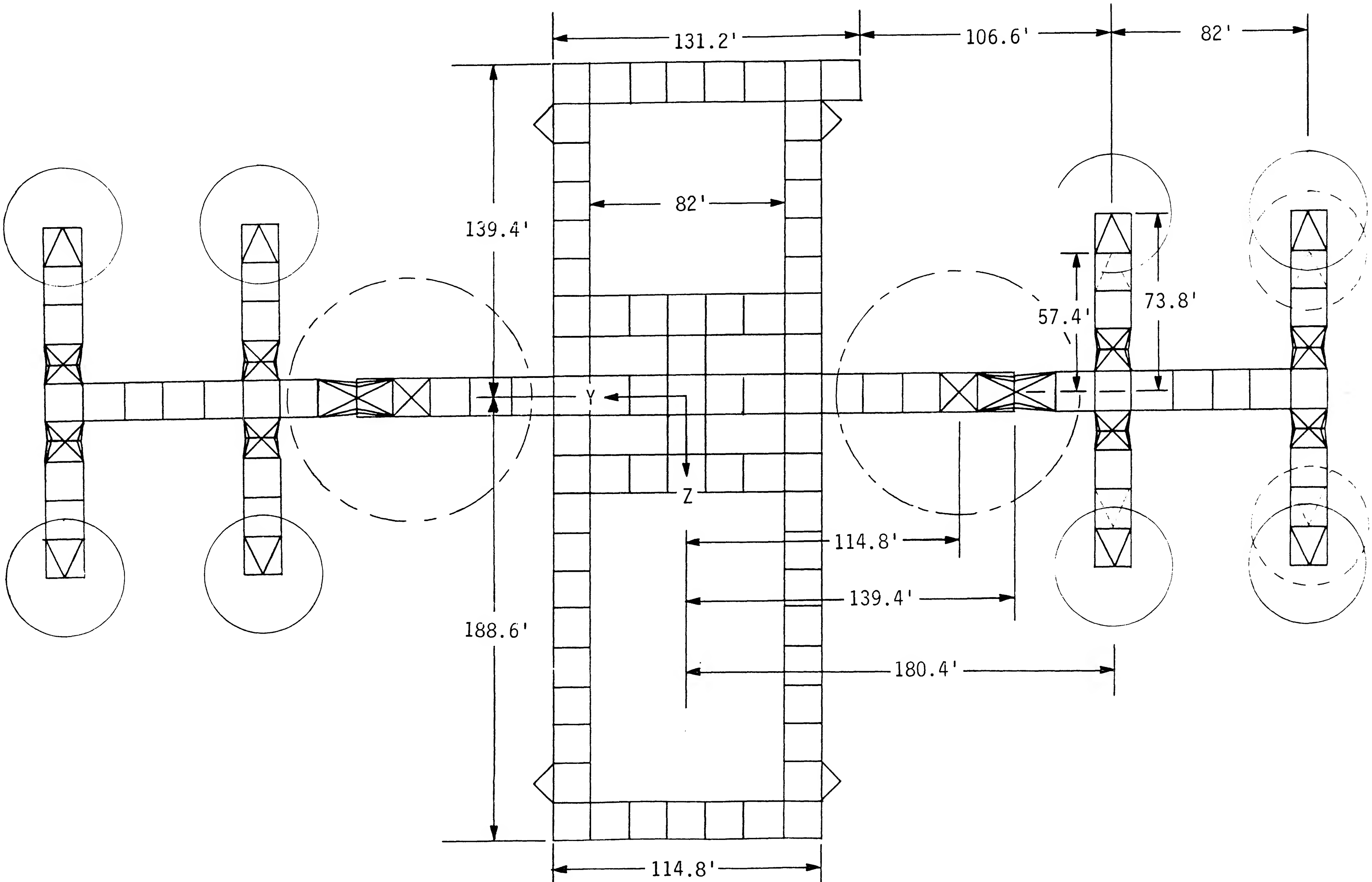


Figure 2.- 5m Truss Dual Keel Space Station.

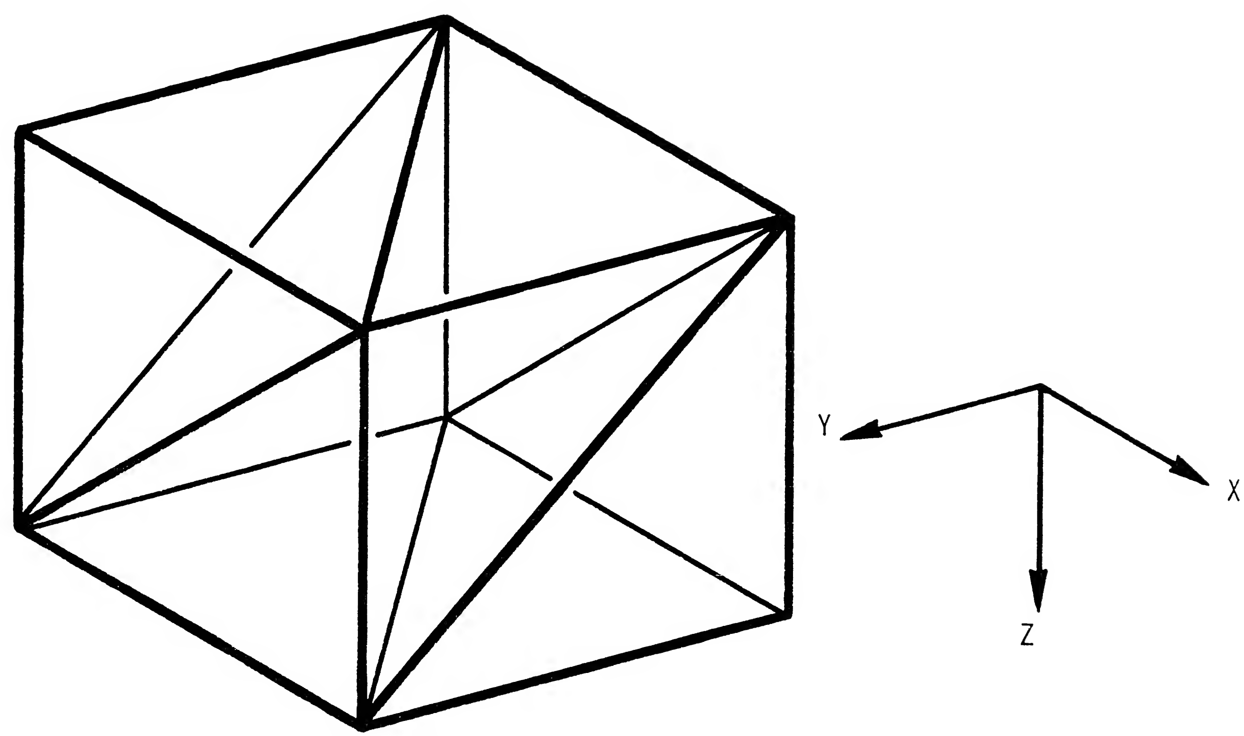


Figure 3.- Reference Orthogonal Tetrahedral Truss Bay.

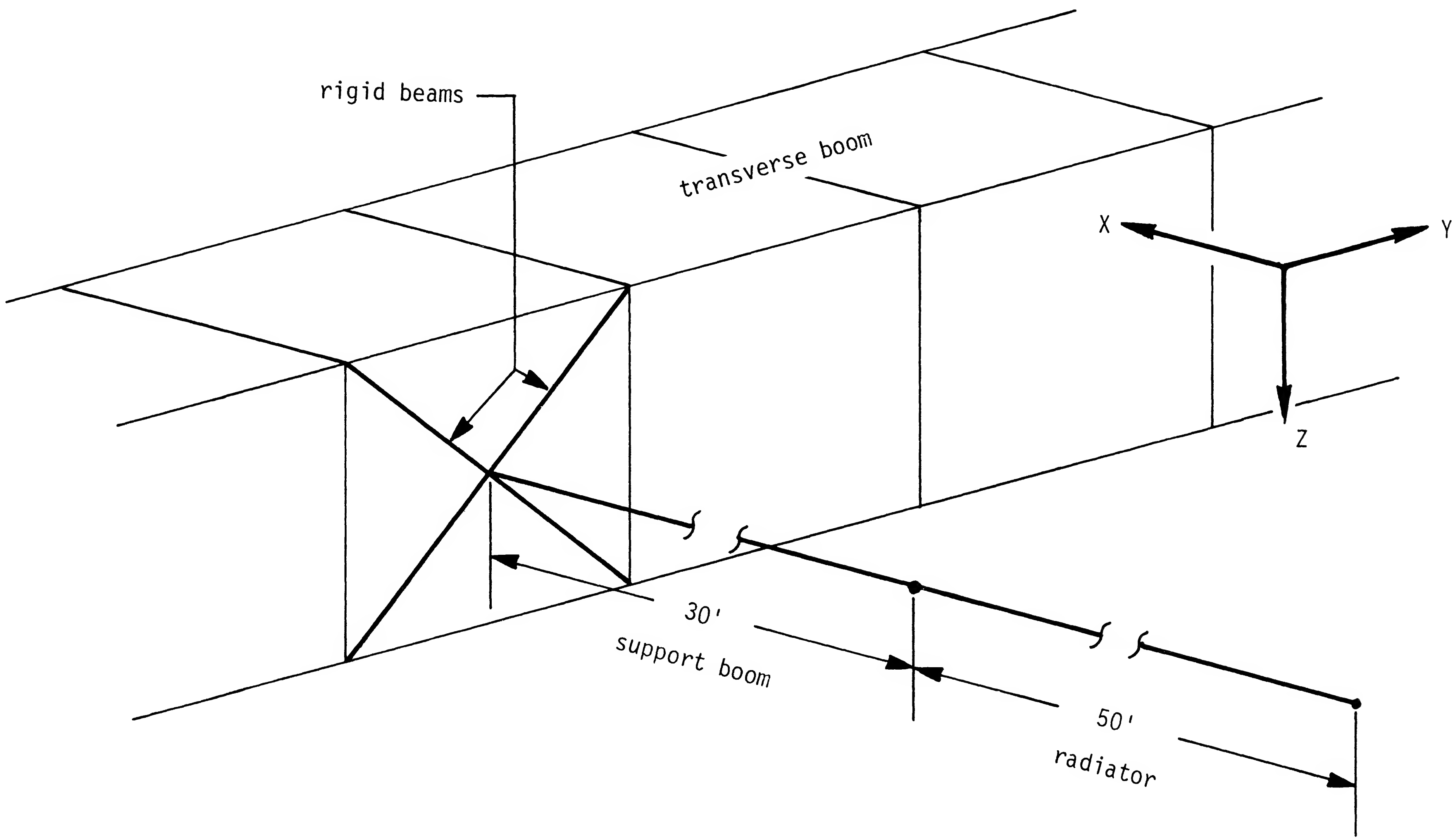


Figure 4.- Central Radiator Detail.

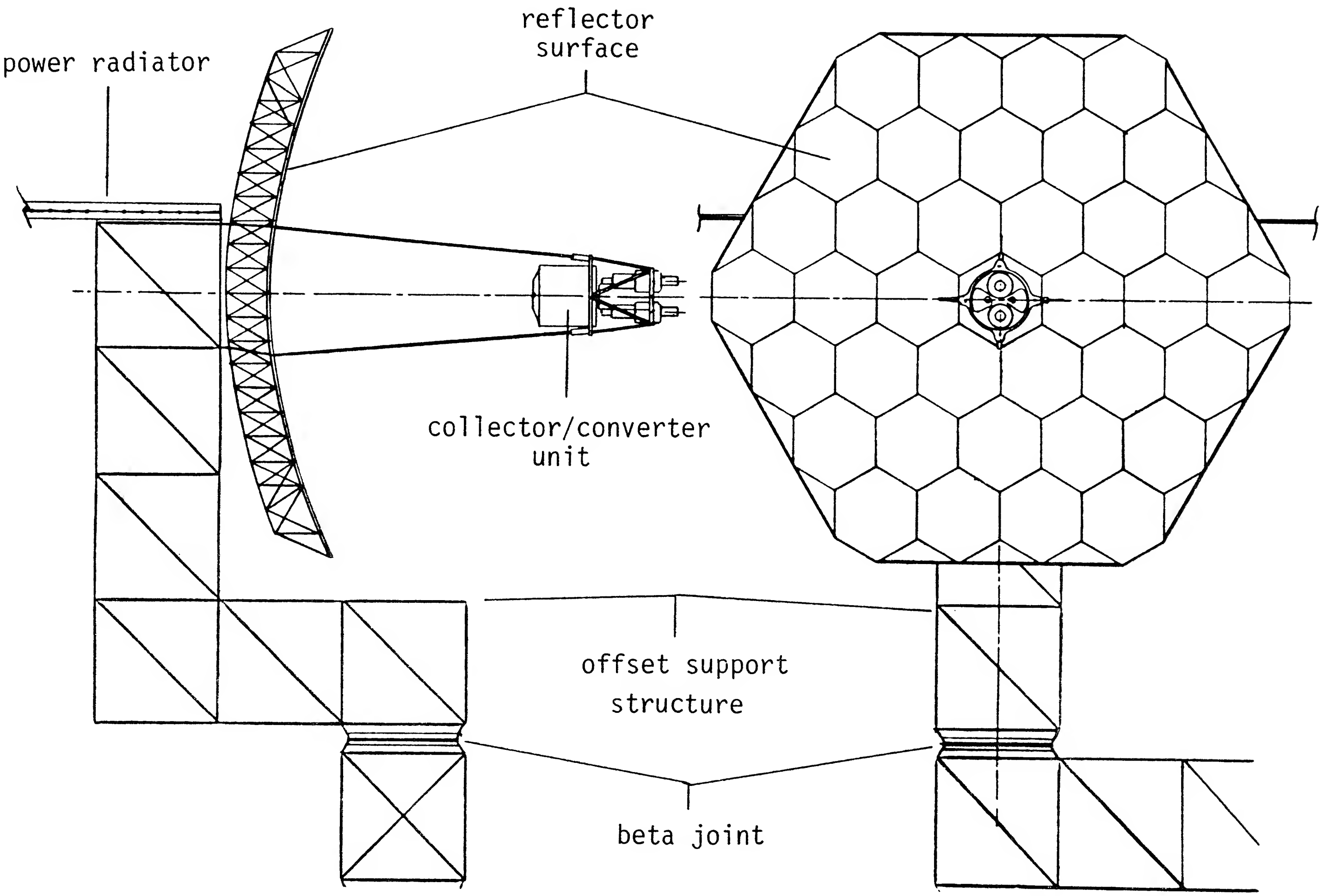


Figure 5. - Typical Solar Dynamic Unit.

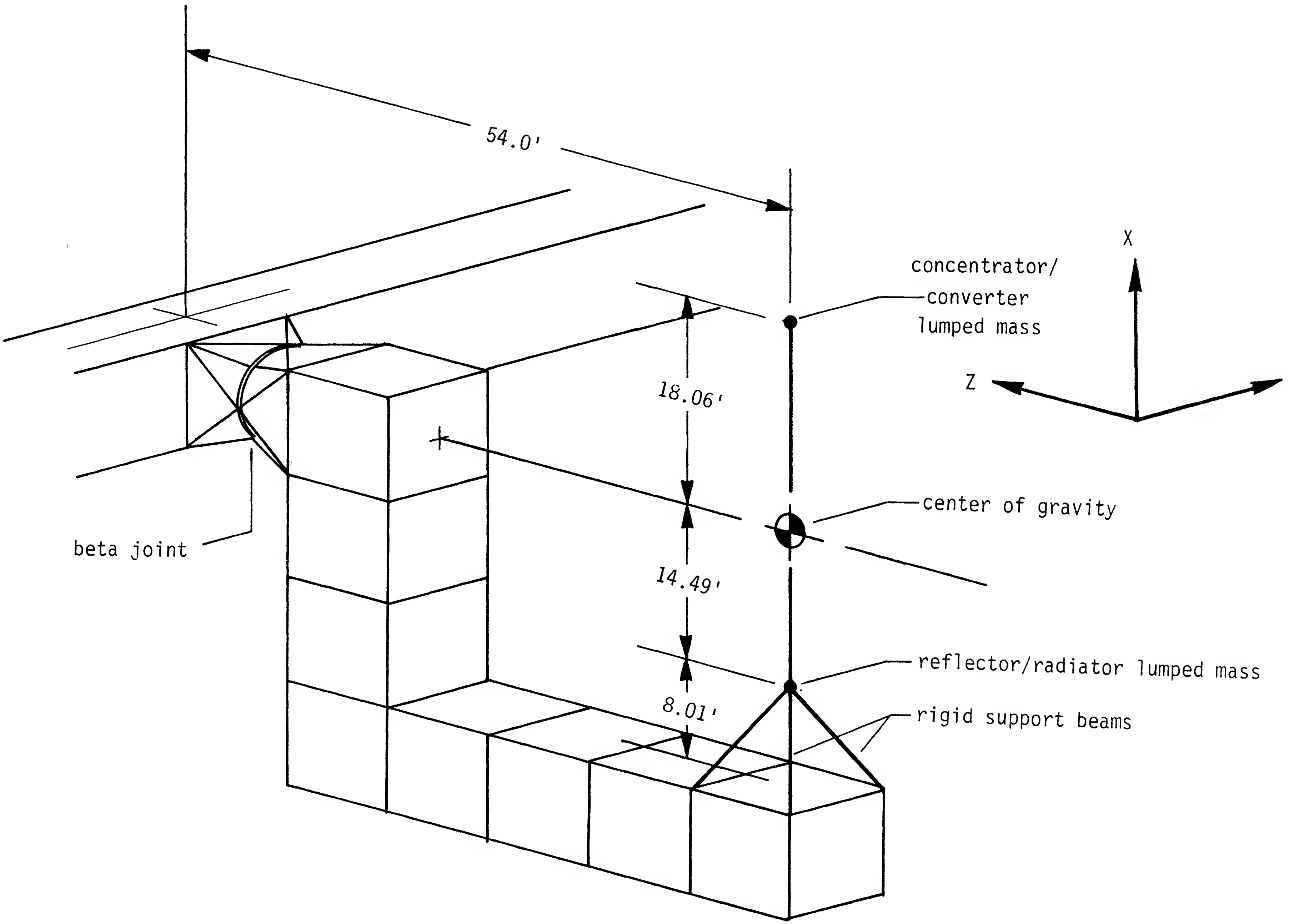


Figure 6.- Solar Dynamic Power Unit - 9' Truss.

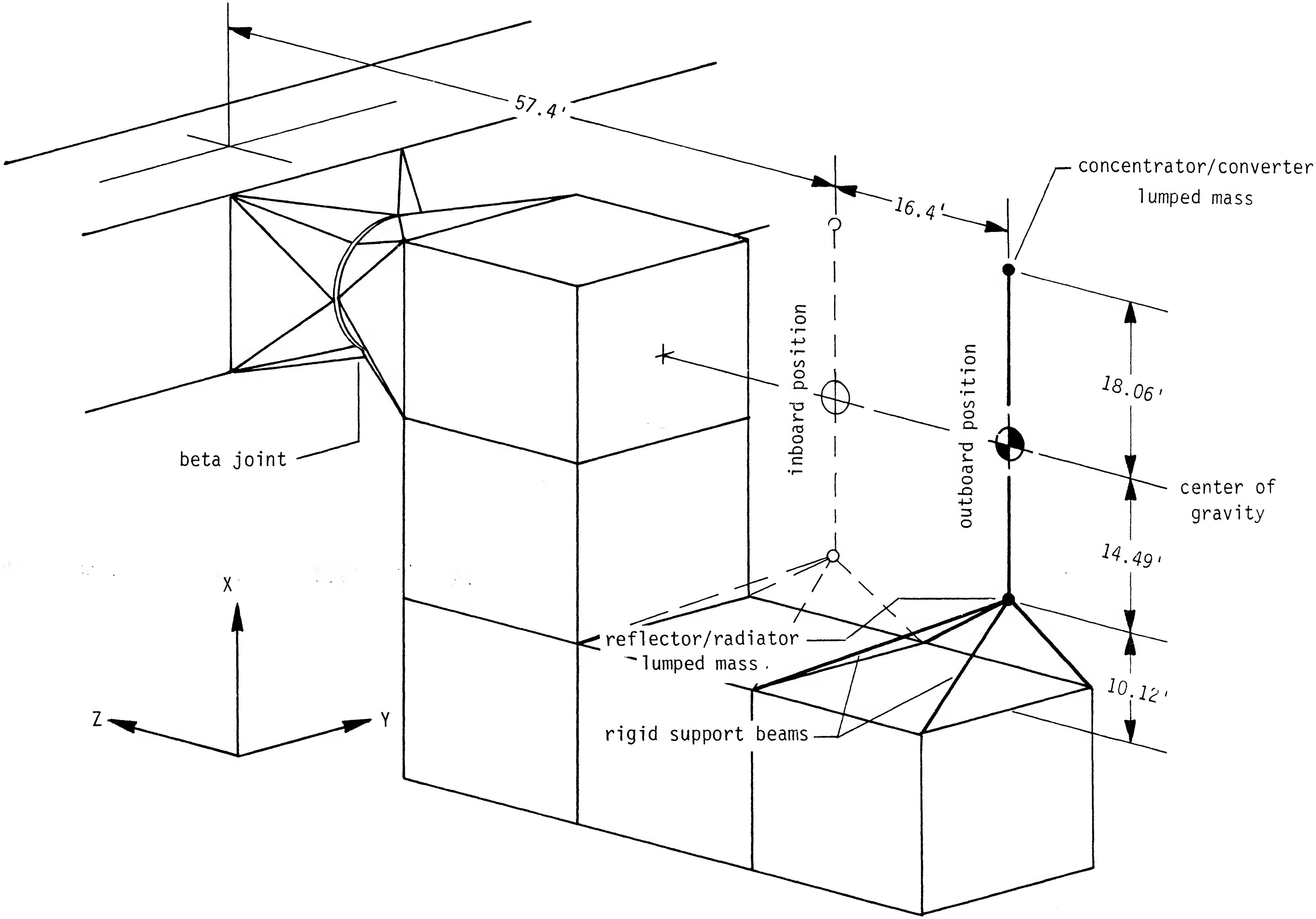


Figure 7.- Solar Dynamic Power Unit - 5m Truss.

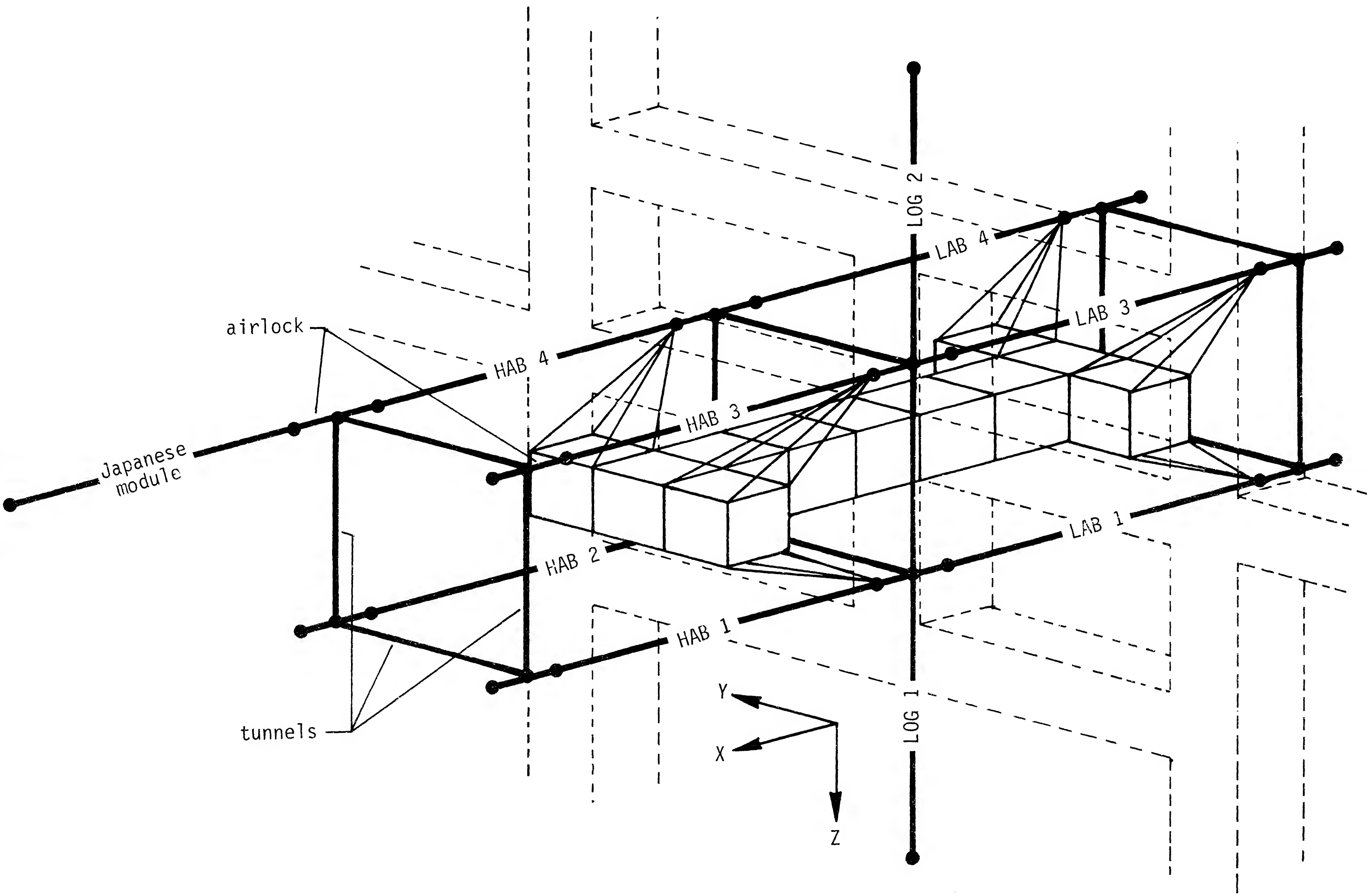


Figure 8.- Module Detail - 9' Truss.

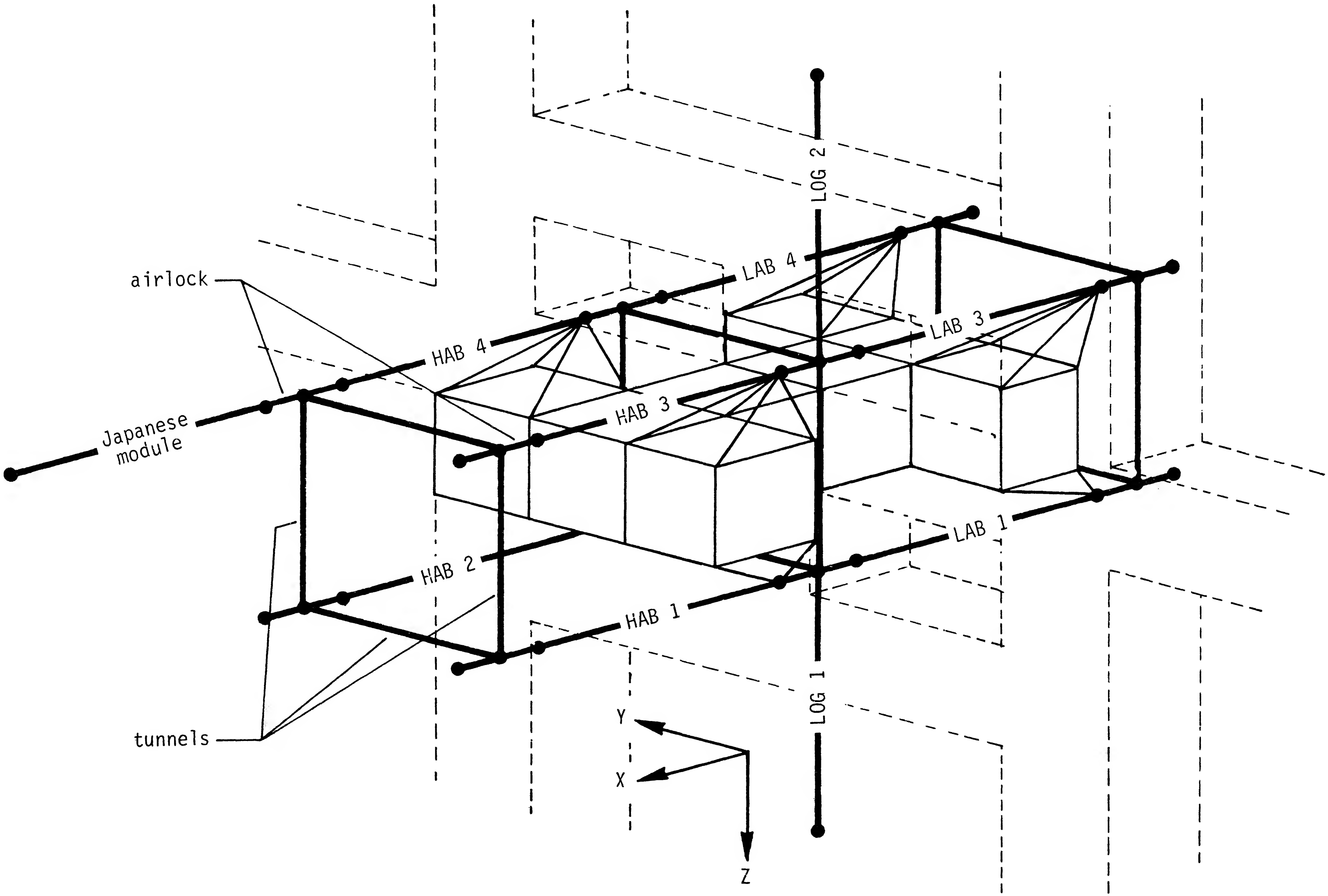


Figure 9.- Module Detail - 5m Truss.

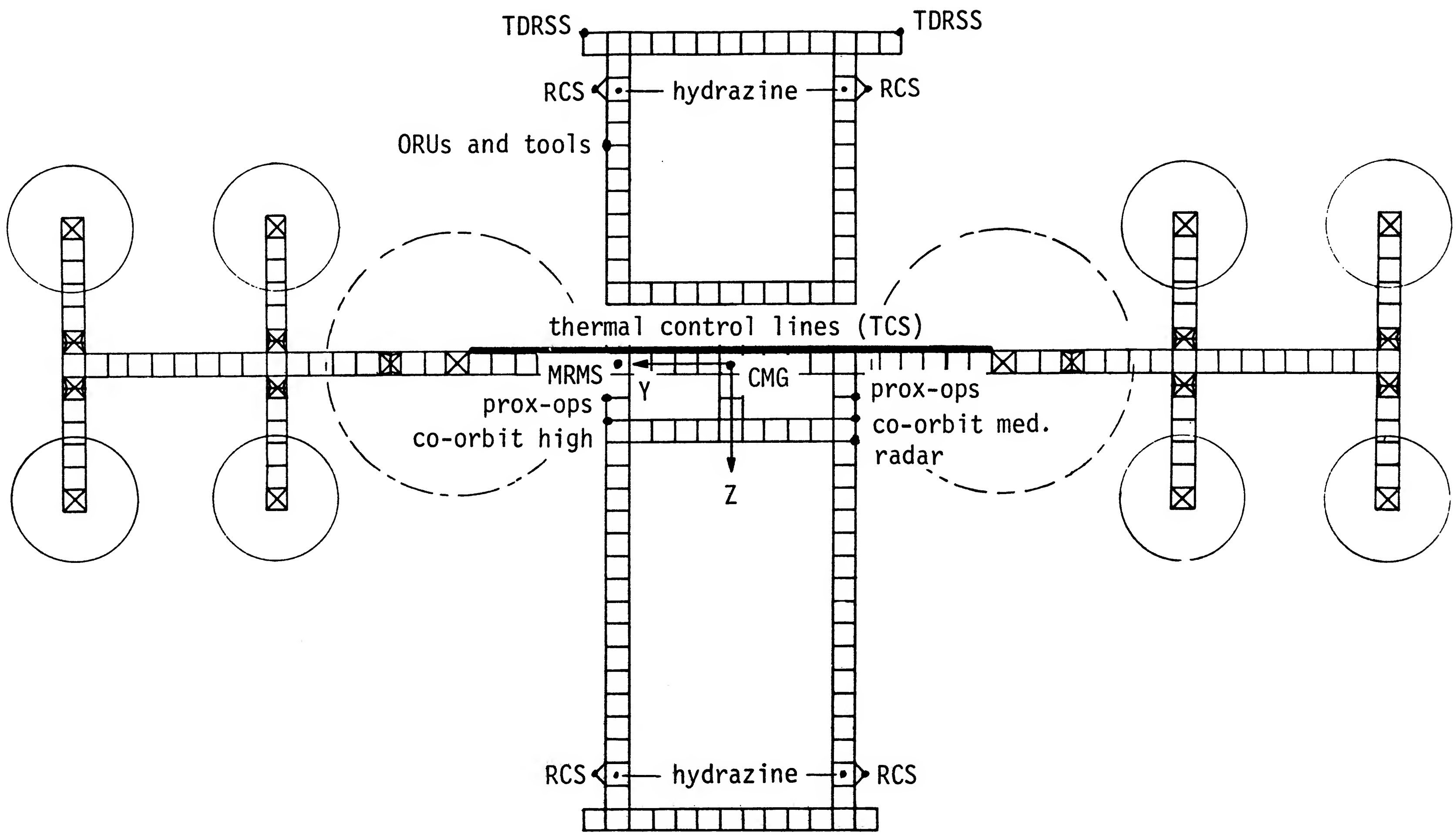


Figure 10.- Subsystem Locations - 9' Truss.

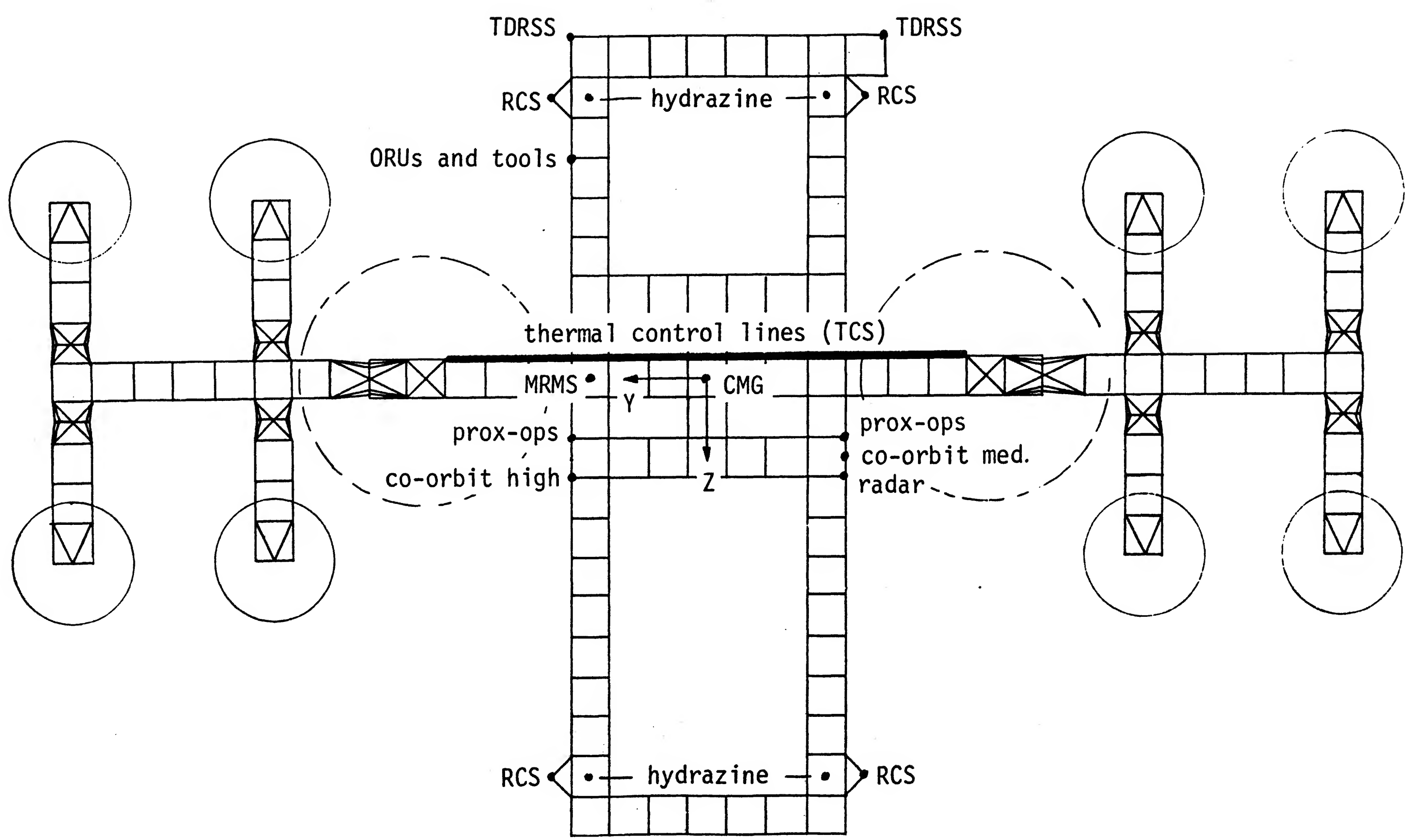


Figure 11.- Subsystem Locations - 5m Truss.

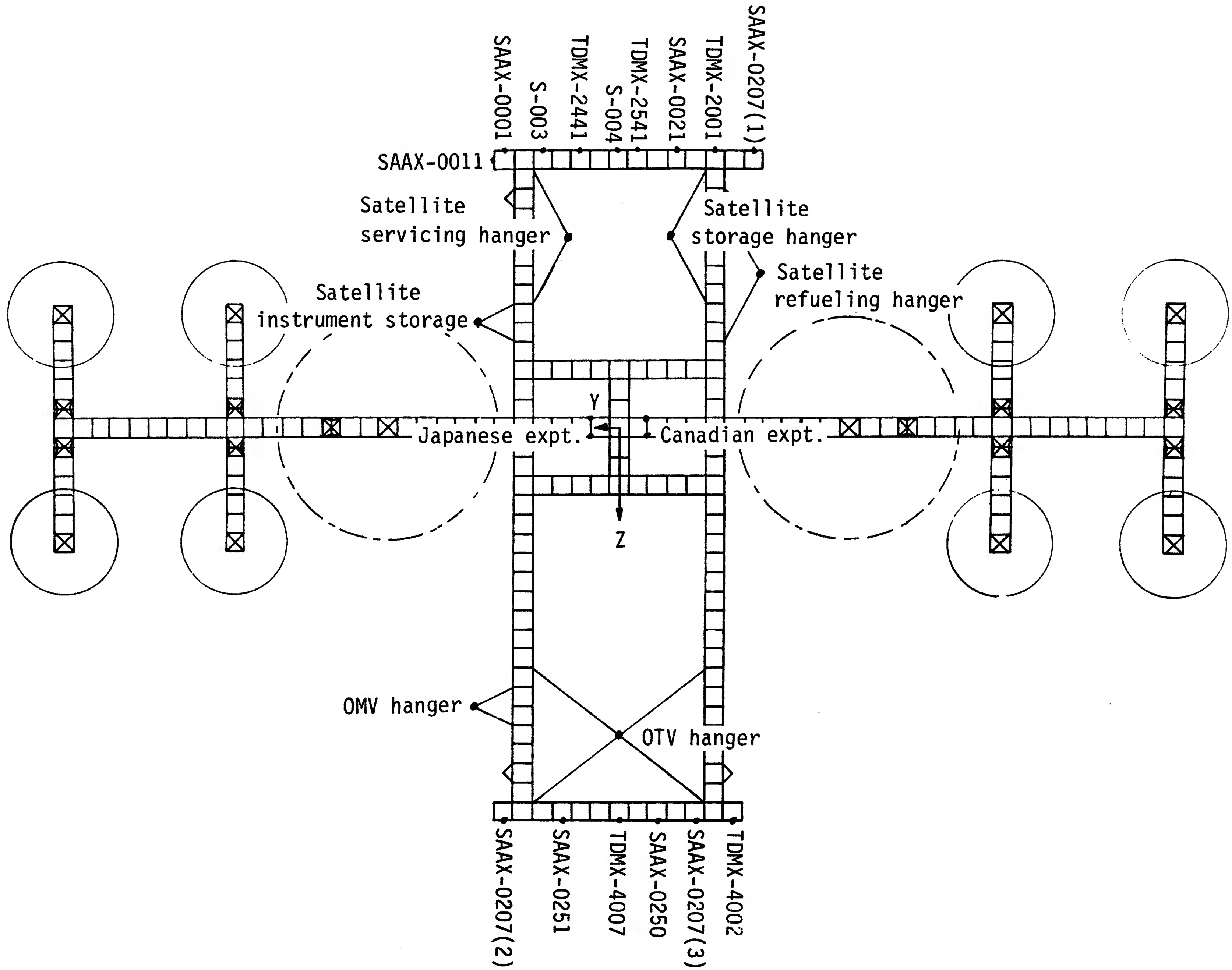


Figure 12.- Payload Locations - 9' Truss.

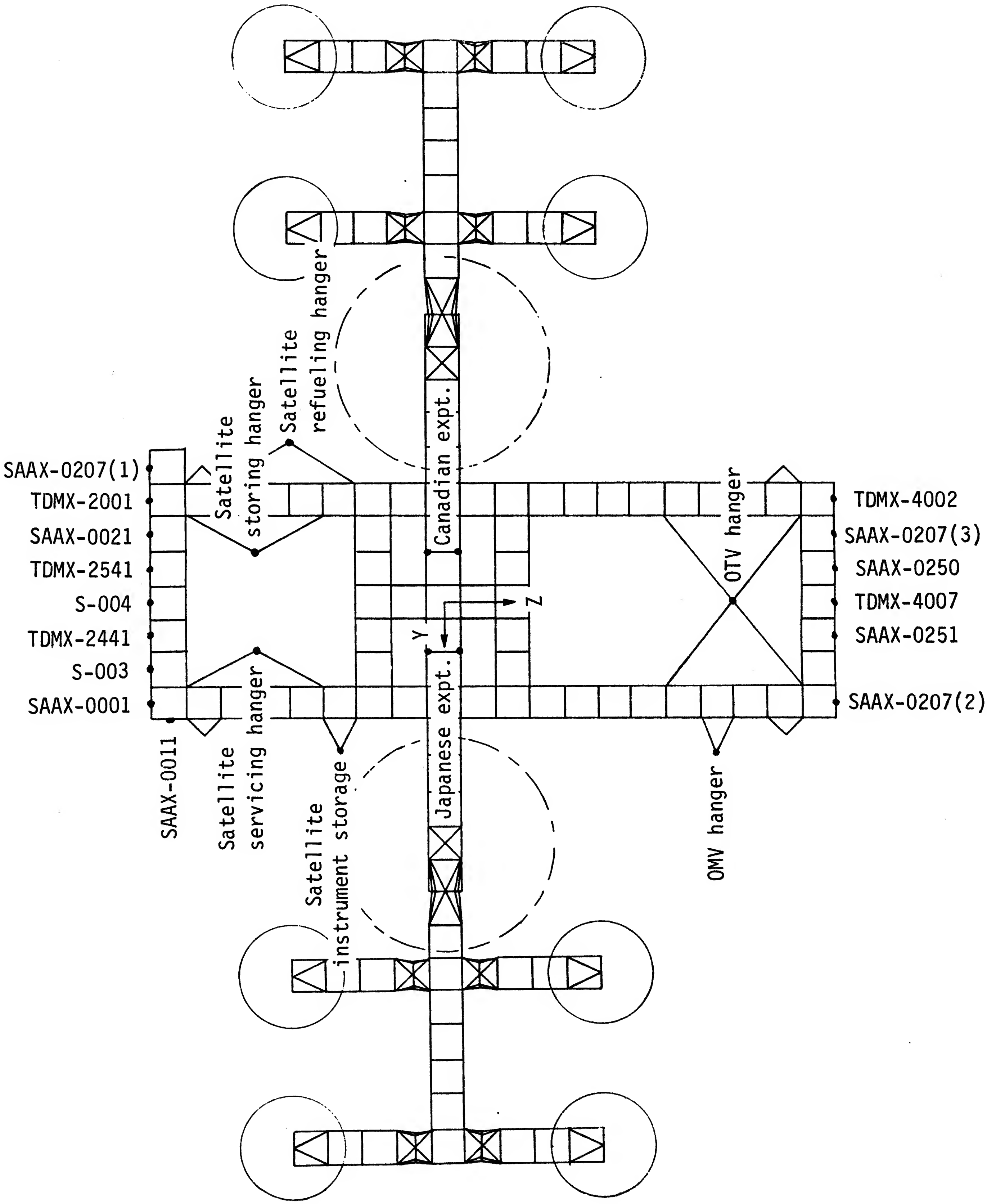
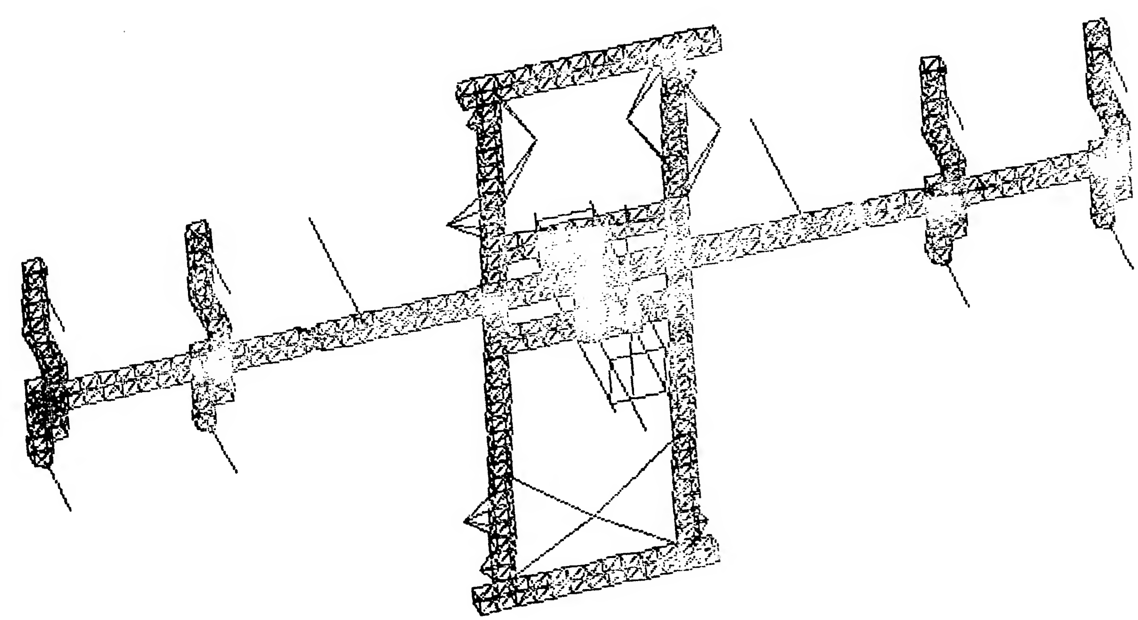
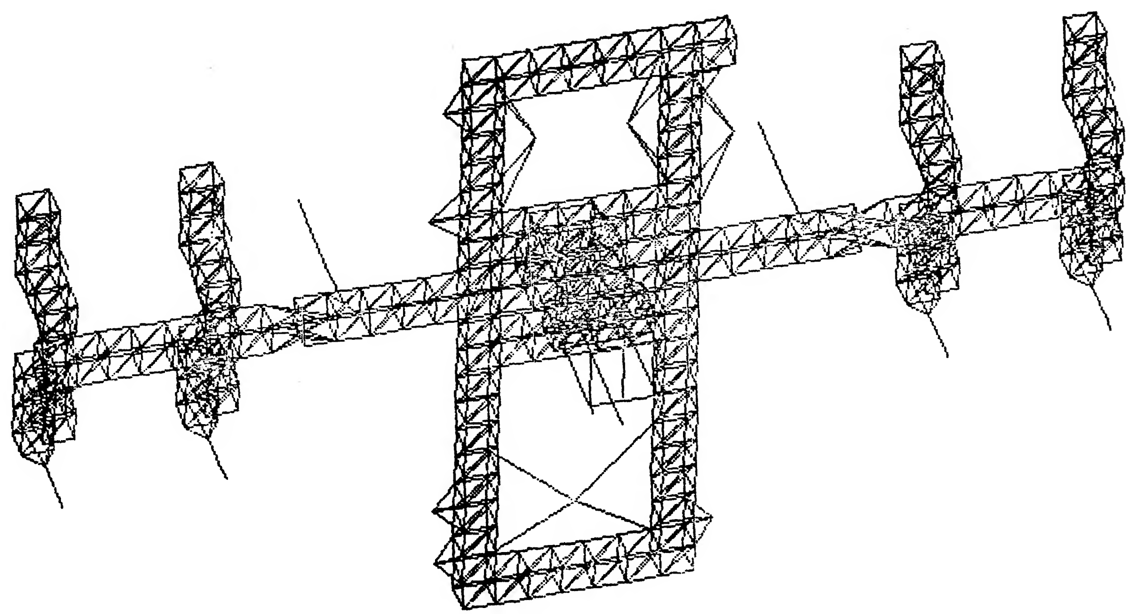


Figure 13.- Payload Locations - 5m Truss.



- 1159 nodes
- 3510 dynamic degrees of freedom
- 235 beam elements
- 3485 truss elements

Figure 14. - Finite element model - 9' truss.



- 735 nodes
- 2238 dynamic degrees of freedom
- 235 beam elements
- 2110 truss elements

Figure 15. - Finite Element Model - 5m truss.

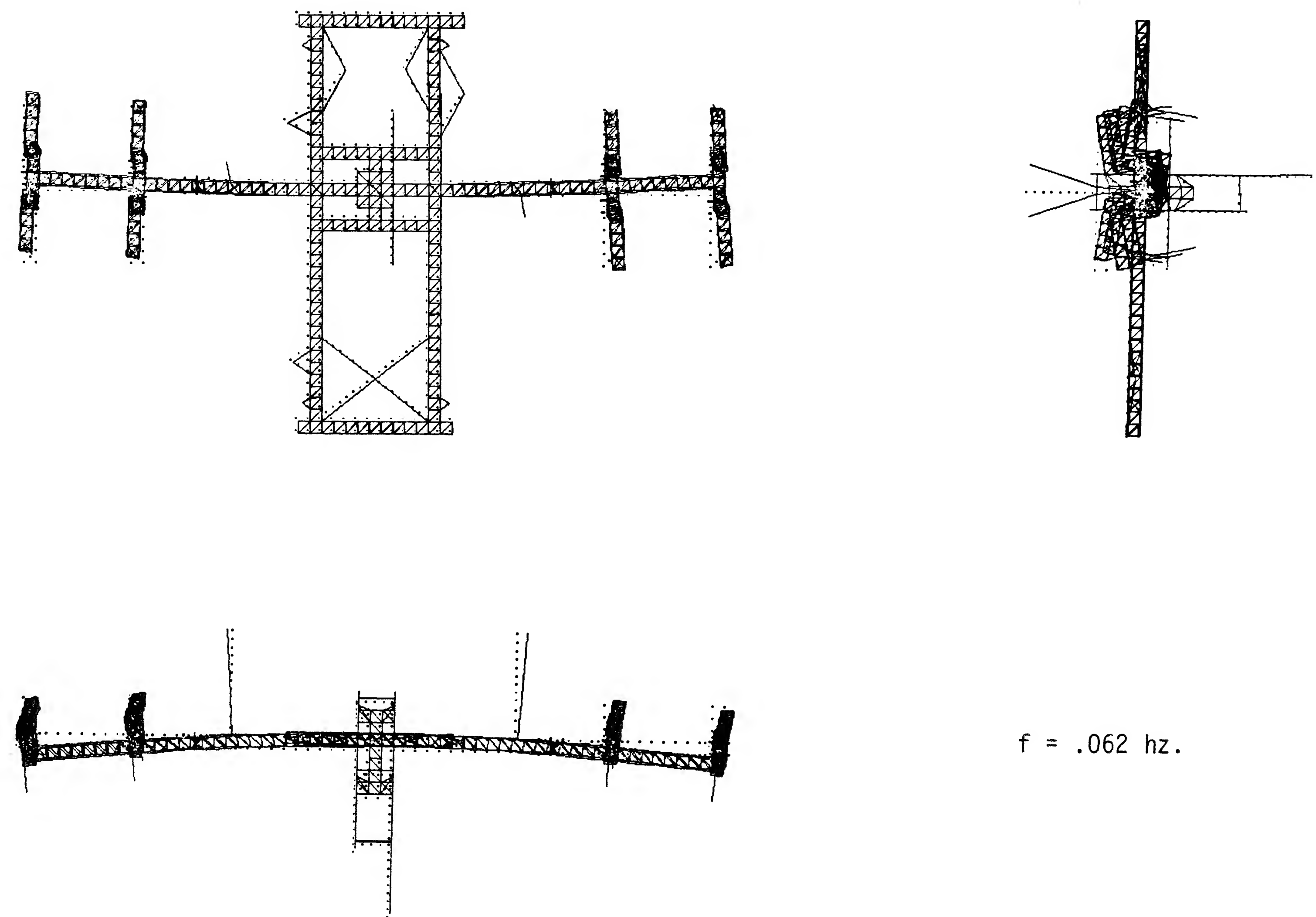


Figure 16a. - Fundamental truss mode for the 9' model.

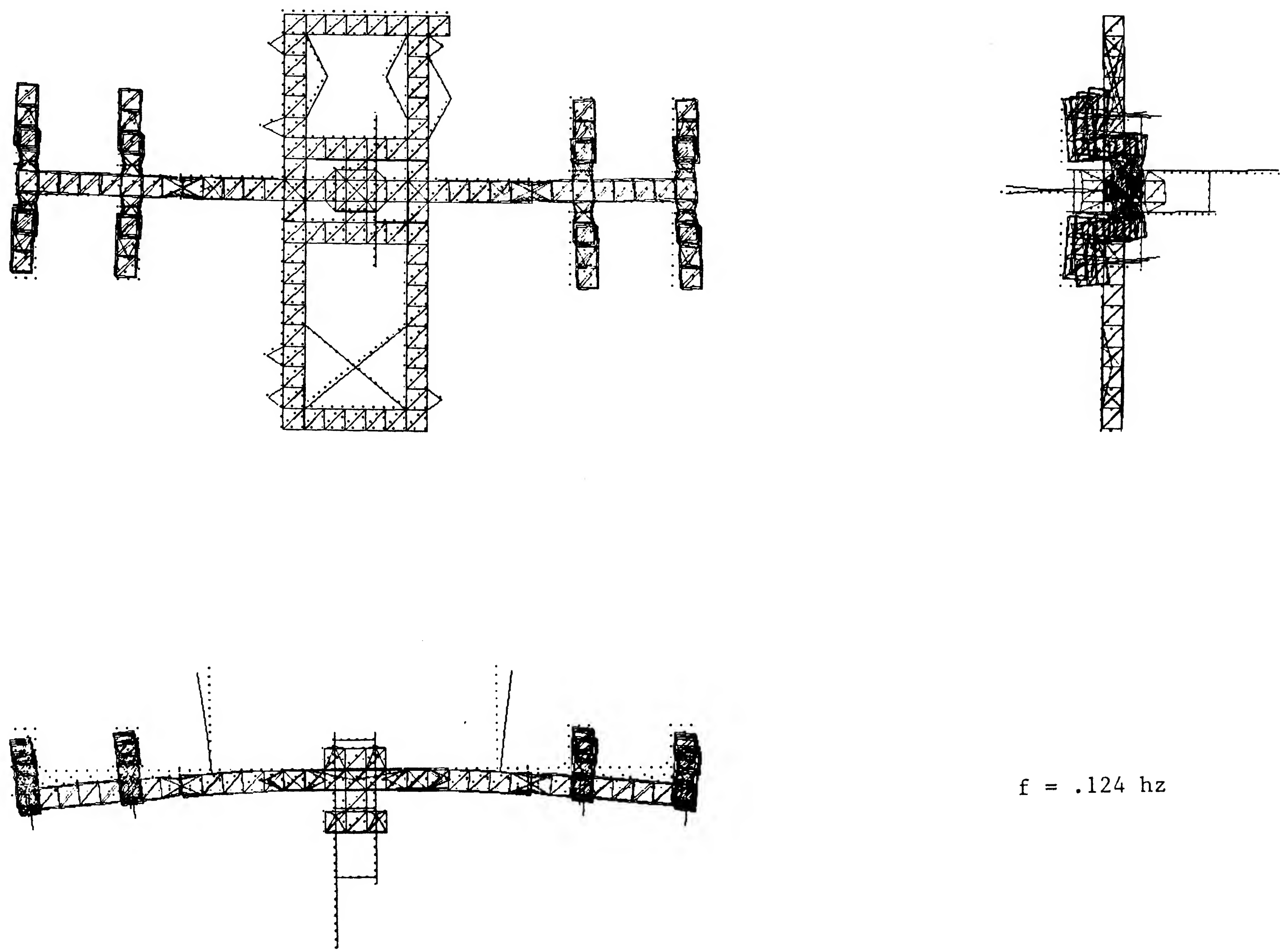


Figure 16b.- Fundamental truss mode for the 5m model (reflectors in).

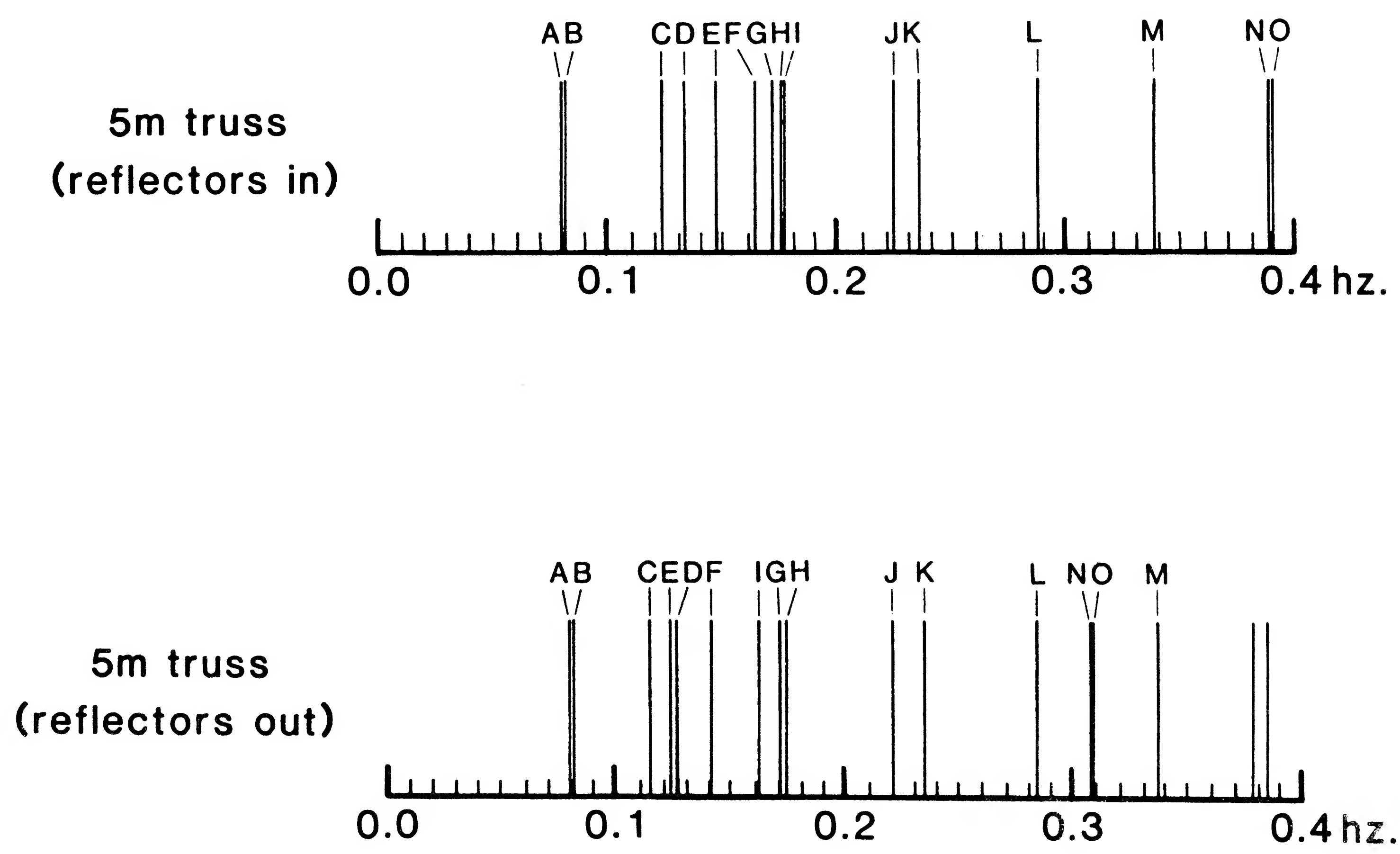


Figure 16C.- Comparison of modes and frequencies for two reflector locations.

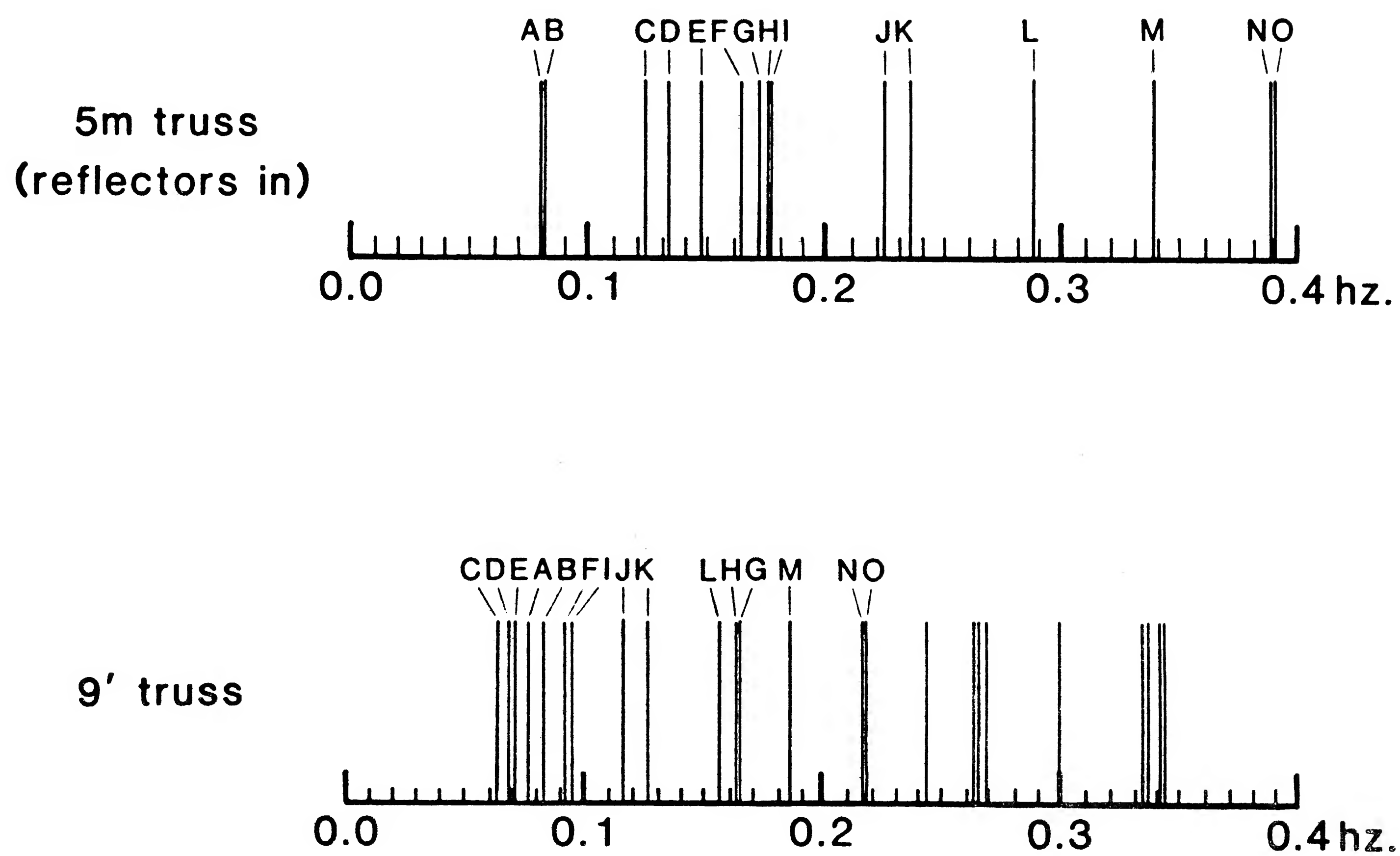
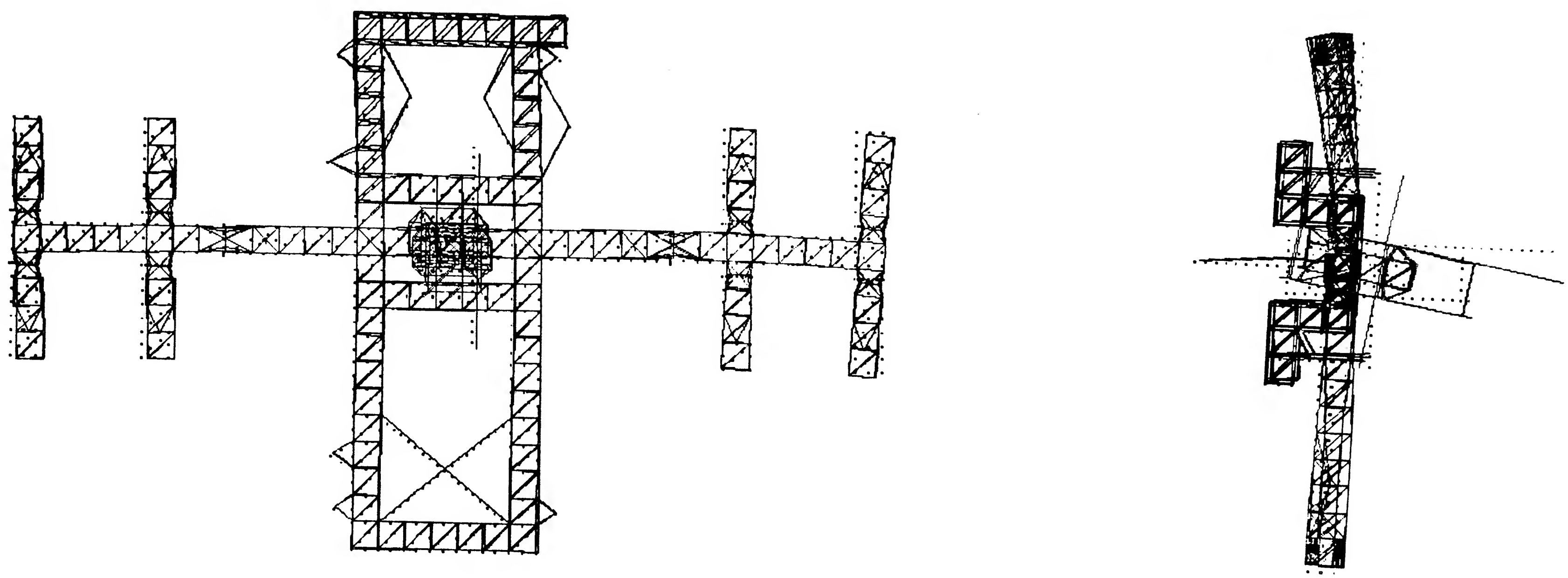


Figure 17A.- Comparison of modes and frequencies for 9' and 5m models.



f = .339 hz

Figure 17b.- Module cluster torsion mode (mode M) for 5m truss (reflectors in).

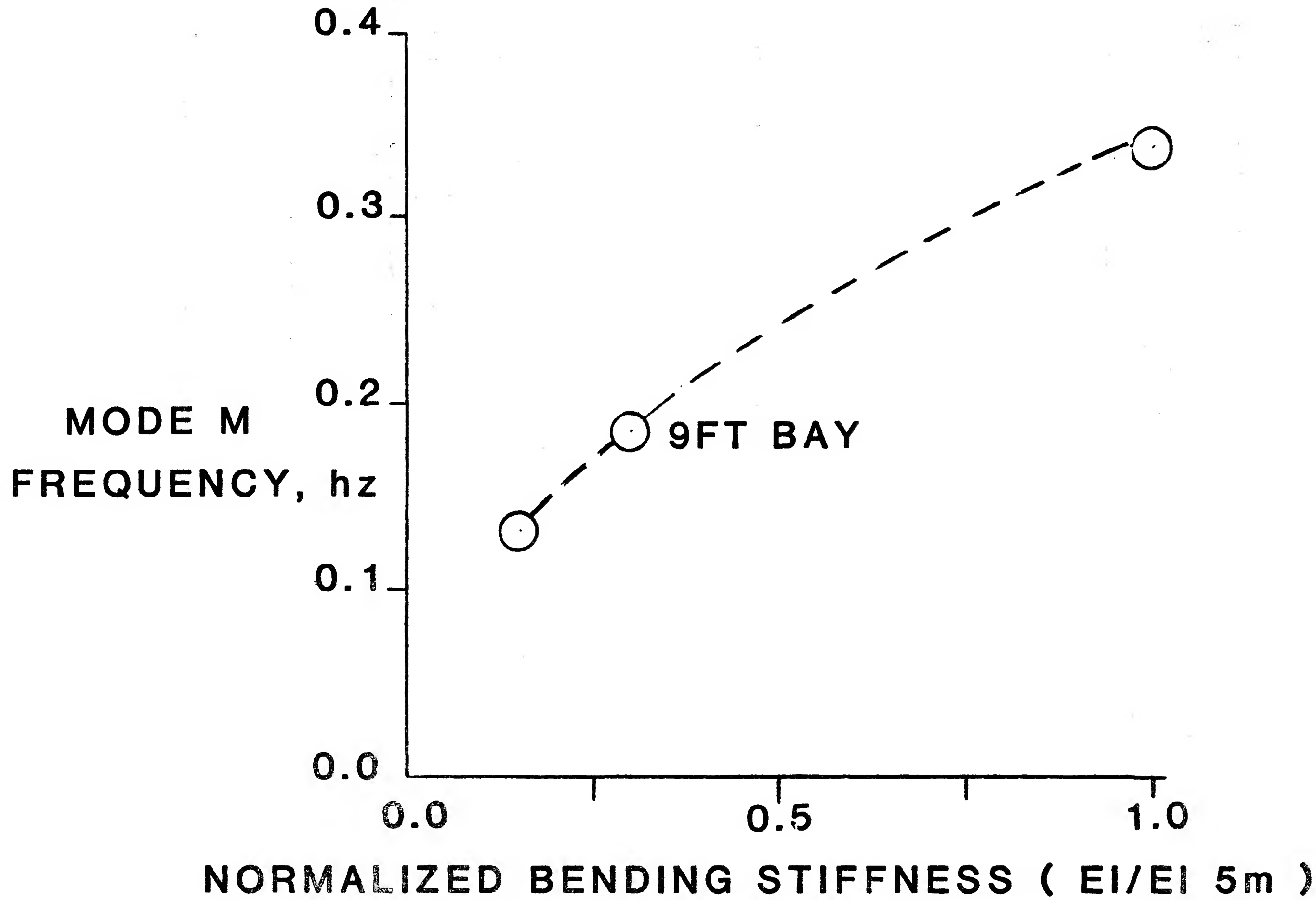


Figure 18.- Mode M frequency versus truss bending stiffness.

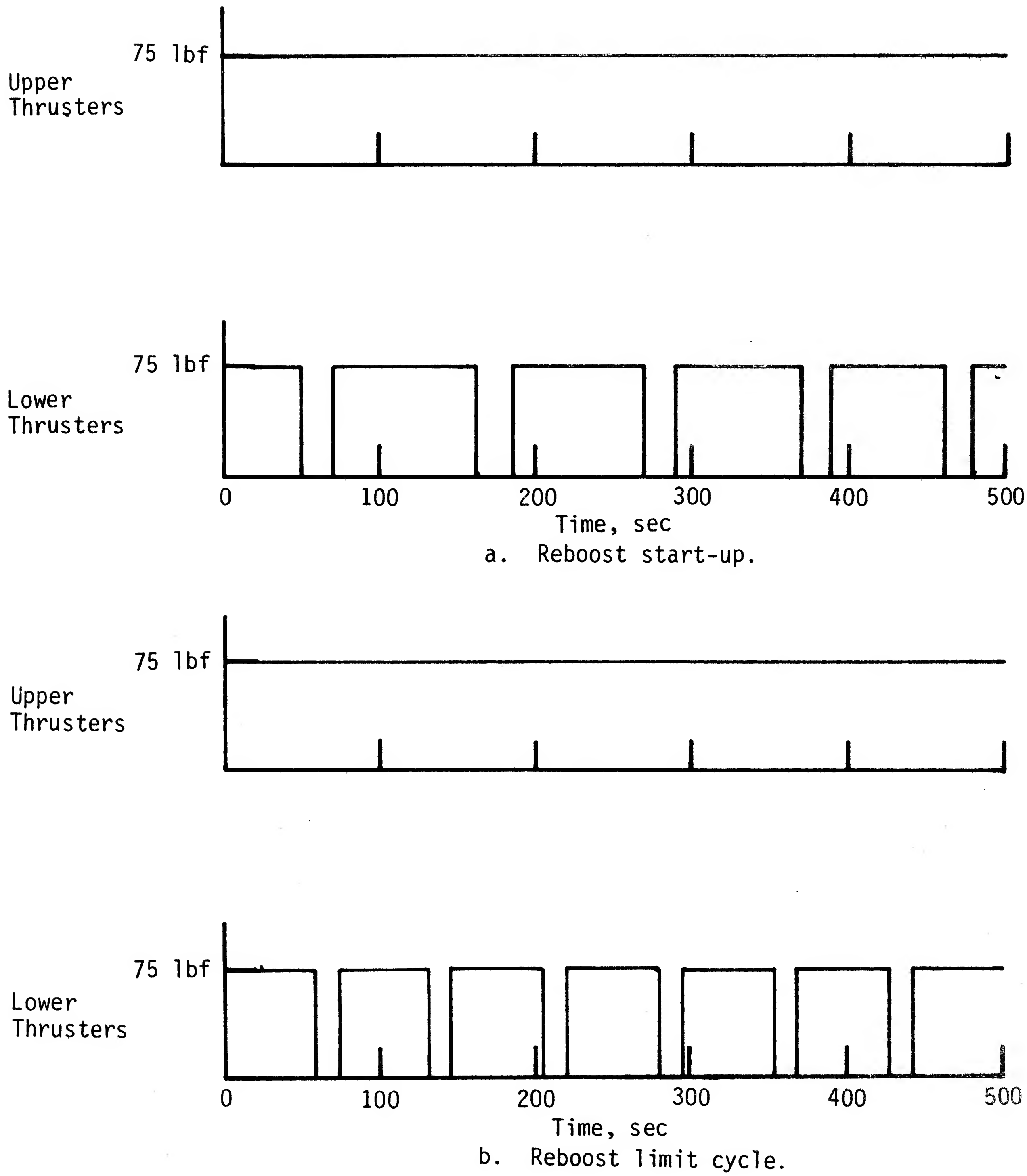
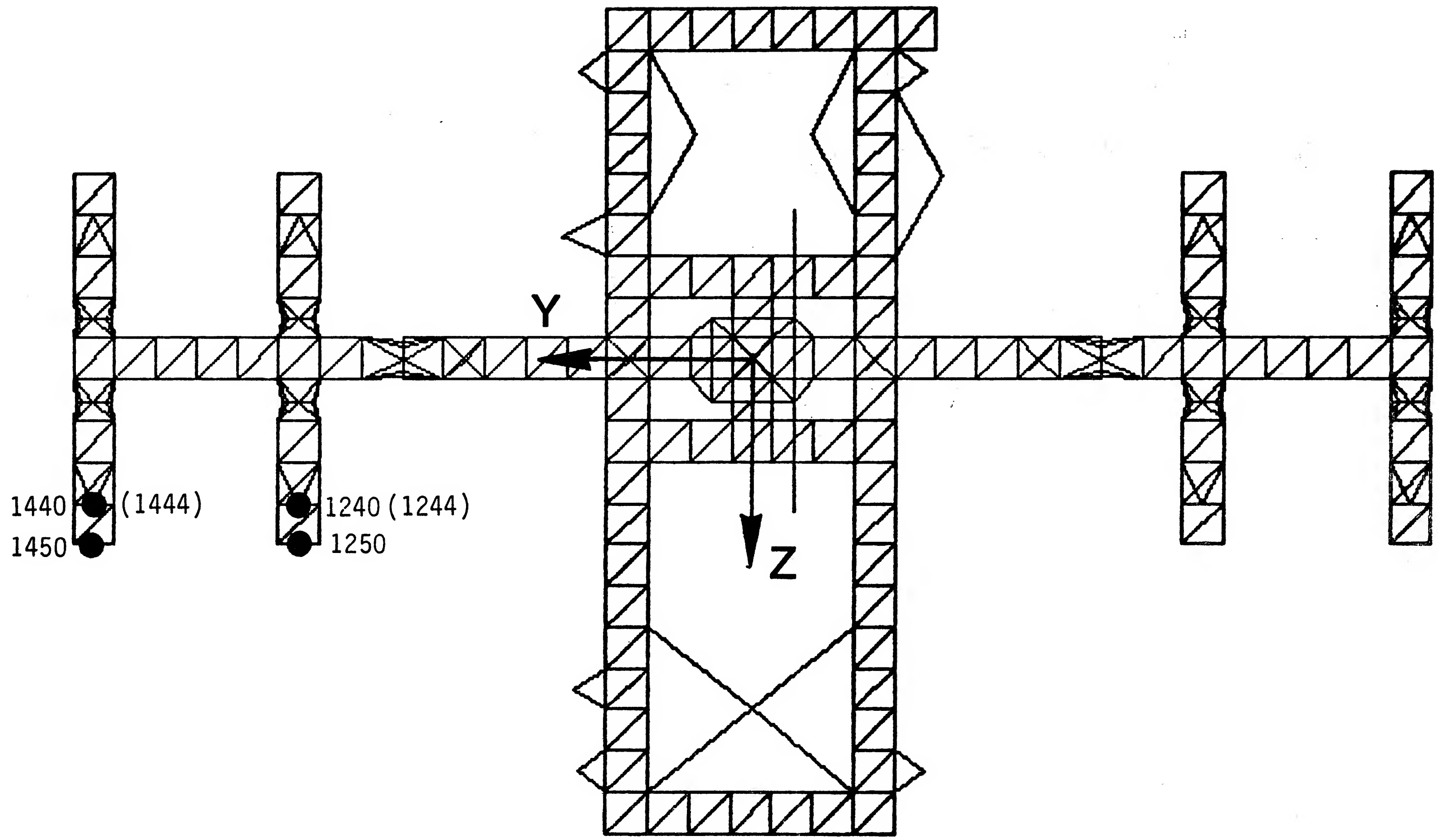


Figure 19.- Orbit reboost firing sequence for station with 5m bays.



Note - Joint labels without parentheses are for the station with 5m bays. Joint labels in parentheses are for the equivalent location on the station with 9' bays.

Figure 20.- Solar dynamic concentrator output joint locations.

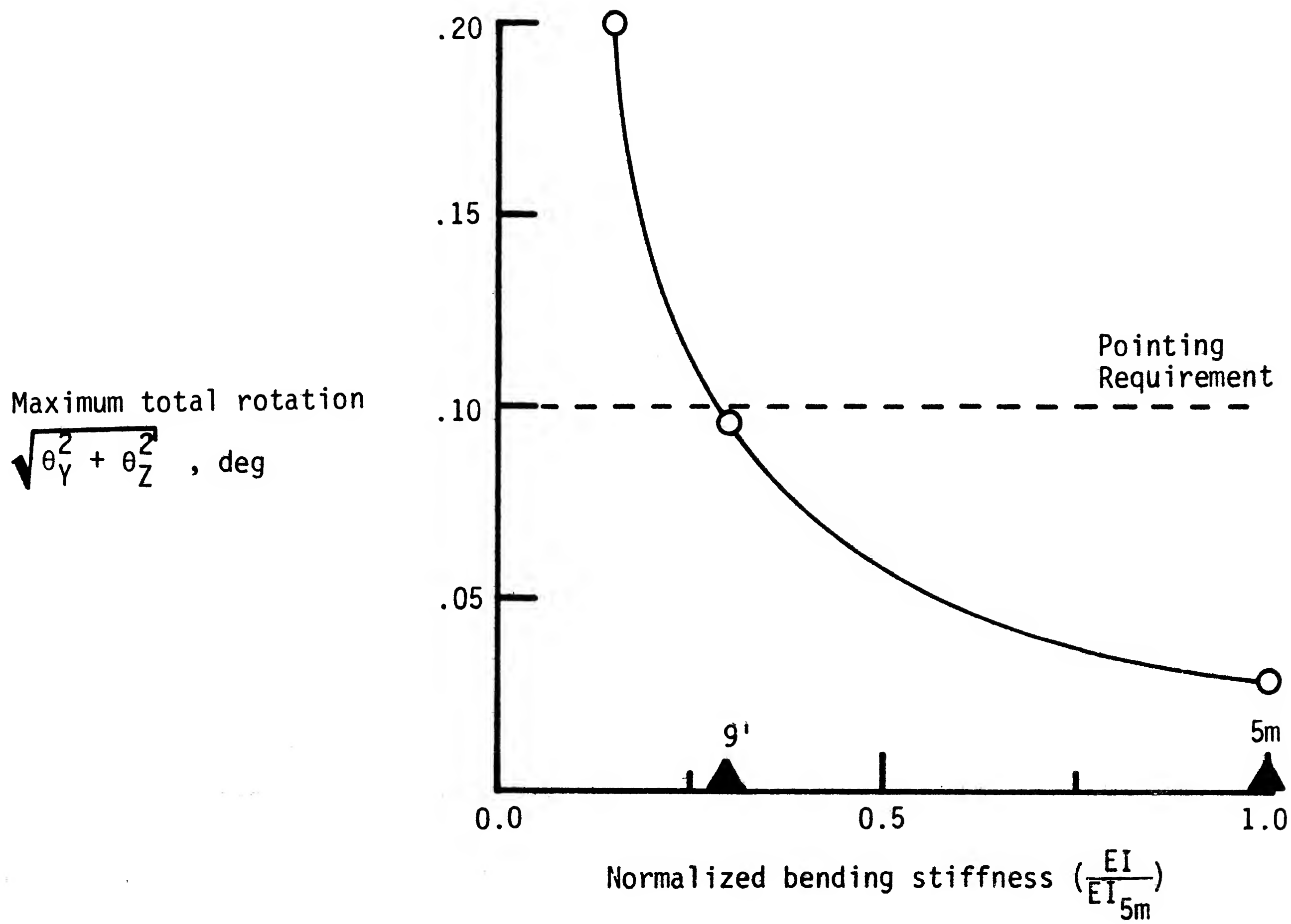


Figure 21.- Maximum outboard solar dynamic concentrator flexible response versus truss bending stiffness.

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16. Abstract

Results from an investigation of the dynamic behavior of a 300 kw class solar dynamic powered, dual keel space station are presented. The purpose of the investigation was to determine and assess the influence of space station truss bay size on station controllability during rigid body attitude adjustment and orbit reboost maneuvers. The dual keel space station concept is defined and two finite element models (one which has a truss bay size of 5m and another with a truss bay size of 9') are described. Rigid and flexible body characteristics of the two space station models are also presented. Finally, results from a transient response analysis, where the stations are subjected to an orbit reboost maneuver, are summarized.

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